THE RELATIONSHIP BETWEEN LITHOSTRATIGRAPHY AND GEOMECHANICAL PROPERTIES OF SARAH FORMATION OUTCROP ANALOGUE, CENTRAL SAUDI ARABIA

BY

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A Thesis Presented to the
DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

GEOLOGY

May 2015

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

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Dedication

I dedicate my dissertation work to

My Father and Mother

For the soul of my grandfather (Elsharief Mohammed Ahmed Al-Arosy)

For my teachers

For my friends

For my Fiancée (Yusra)

ACKNOWLEDGMENTS

Firstly, I would like to thank Allah for giving me Patience, health and strength to complete this work. Thanks to King Fahd University of Petroleum & Minerals for granting me this scholarship and supporting my research. I would like to express my thanks to my Committee Chairman, Dr. Osman Abdullatif for great effort and guidance. Great thanks to my committee members Prof. Gabor Korvin and Dr. Mustafa M. Hariri for guidance and support. Thanks to Dr. Abdulaziz Al-Shaibani, the chairman of Earth Sciences Department. I am also grateful to all the department's faculty members for teaching, support and guidance. Also I would like to acknoldge the support provided to the work by the reservoir characterization group project #RG# 1418.

Acknowledgements extended to all my colleagues in the department; students, technicians and staff for helping me in the field and laboratory work. Special thanks for Sudanese community in KFUPM. Great thanks to my family and Yusra for great support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Full Name: Jarrah Mohmmed Ahmed Mubark

Thesis Title: The Relationship between Lithostratigraphy and Geomechanical Properties of Sarah Formation Outcrop Analogue, Central Saudi Arabia.

Major Field: Geology

Date of Degree: April 2015

The Late Ordovician Sarah Formation is glacio-fluvial deposits outcropping in north and central Saudi Arabia. Sarah Formation covers wide area in the subsurface, and is considered as important target for conventional and tight gas reservoir in the subsurface. This study characterizes the lithofacies, sedimentological and fracture characteristics of the Sarah paleovalley and also to investigate the relationship between lithostratigraphy and geomechanical properties. The work included three parts which are, field investigation, laboratory part and analytical part. The field work investigated the sedimentological and geomechanical heterogeneity of the paleochannel and fracture characteristics through vertical and lateral outcrop sections at different locations within the paleochannel. The laboratory analysis included thin section petrography, XRD, SEM, and petrophysical analyses (porosity and permeability) and the geomechanical measurements (point load, uniaxial compressive strength, velocity measurements). The analytical part investigated the lithological heterogeneity from macro to micro scale and also investigated the relationship between the lithological, petrophysical and the geomechanical properties. The study revealed five lithofacies within the paleovalley that included (a) yellowish brown, poorly sorted, medium to coarse diamictite interbedded with ferruginous sandstone (b) brownish yellow, finely laminated, slumped siltstone lithofacies (c) slumped mudstone lihofacies, (d) white, medium to coarse grained, diamictite and poorly sorted sandstone and (e) yellow, fine to medium grained moderately sorted, laminated fluvial sandstone lithofacies. The paleochannel showed micro- to macro scale sedimentological heterogeneity and architecture. The fracture analysis revealed on three types of fracture modes which are, mode 1 (opening mode), mode 2 (sliding mode) and mode 3 (shear mode) which all reflect different stress regimes. Both calcite and iron oxides are found as fracture fill for most of the closed to resistive fracture types (mode 2 and mode 3 fracture types). A geological model was constructed by integrating sedimentological and structural features based on field observation and laboratory analysis. The study also revealed five geomechanical units which have direct relationship to the lithological units and ranging between low strength to extremely low strength units. This study helped to understand the sedimentological, channel architecture and fracture characteristics and geomechanical properties and heterogeneity of the glacio-fluvial paleochannel of Sarah Formation. The outcrop analogue results might also help to understand, predict and evaluate Sarah Formation glacio-fluvial reservoirs heterogeneity, quality in the subsurface.

ملخص الرسالة

الاسم الكامل: جراح محمد احمد مبارك

عنوان الرسالة: دراسة العلاقة بين التتابع الطبقي والخصائص الجوميكانيكية لمتكون ساره, وسط المملكة العربية السعودية

التخصص: جيولوجيا

تاريخ الدرجة العلمية : أبريل2015

يعتبر متكون ساره اوردفيشي في العمر يحتوي علي رسوبيات جليدية الي جليدية نهرية يظهر في وسط وشمال المملكه العربية السعودية. متكون ساره يغطي مساحة كبيرة تحت السطح ويعتبر هدفا للغاز الصخري والبترول. الهدف من هذه الدراسة هو دراسة العلاقة بين التتابع الطبقي والخصائص الجوميكانيكية, دراسة التكوينات الرسوبية وخصائص الطبقات لمتكون ساره الجليدي و كذلك لدراسة الشقوق التركيبية ومميزاتها لمتكون ساره الجليدي في منطقة القصيم في روض الجواء. هذه الدراسة تحتوي علي ثلاثة أجزاء رئيسية وهي الدراسة الحقليه, والدراسة المعمليه والدراسة التحليلية. الدراسة الحقليةتهدف الي دراسة التكوينات الرسوبية والطبقات وتهدف الي دراسة الخصائص الجيوميكانيكية للطبقات الرسوبية قيد الدرسة وكذلك تهدف الي دراسة الشقوق التركيبية لمتكون ساره من خلال دراسة أربعة مقاطع رأسية متوزعة في مناطق مختلفة في متكون ساره. التحليل المعملي استكشف الخصائص الدقيقة للرسوبيات الموجوده في منطقة الدراسة وكذلك دراسة الخصائص الفيزيائية للصخور من خلال دراسة المساميه والنفاذية لصخور متكون ساره ودراسة الخصائص الميكانيكية للمتكون. الجزء التحليلي لهذه الدراسة استكشف التنوع الرسوبي والترسيبي للصخور علي مستوي المكشف ومستوي الشرائح ومستوي عينة اليد.

. نتائج دراسة الرسوبيات أظهرت خمسة سحنات رسوبية لها خصائص رسوبية مختلفة وهي الحجر الرملي اصفر اللون, السحنة الطيبية , صحنة الطمي البني, والحجر الرملي الأبيض, وأخيرا سحنة الحجر الرملي نهري المصدر. الدراسات الرسوبية وصفت التغيرات الافقية والراسية من حيث التركيب البنائي الرسوبي ومن حيث امتداد الطبقات الرسوبيه للمكشف الجليدي ويمكن ملاحظة هذه التغيرات علي مستوي المكشف او عينة اليد او علي مستوي الشرائح الرقيقة. الشقوق التركيبية تمت دراستها وكشفت عن ثلاثة أنواع من نسق التشويه التركيبي متوزعة علي مستوي المكشف حيث النسق

الأول ينتج من حركة البينات الصخري بعيدا من بعضها البعض والنسق الثاني ينتج من حركة البنيات الصخرية في اتجاهين مختلفين والنسق الثالث ينتج من حركة البنيات الصخرية بزاوية. كذلك تمت دراسة المعادن والصخور التي تملا هذه الشقوق وعلاقتها بجودة المكمن الرسوبي علي مستوي المكشف وعينة اليد و الشرائح الرقيقة وتبين انها تتكون من اكاسيد الحديد والكالسايت وهي تملا بالتحديد النسقين الثاني والثالث نتيجة للاحتكاك. النتائج التي نجمت من هذه الدراسة ساعدت علي فهم البنا الهيكلي والرسوبي للمتكونات النهرية الجليدية وتوزيعها. دراسة الشقوق التركيبية ساعدنا علي فهم طبيعة هذه الشقوق التركيبية في صخور للبيئة الجليدية وعلاقتها بجوده المكمن الرسوبي. دراسة العلاقة بين الخصائص الجيوميكانيكة والتكوين الرسوبي في هذه الدراسة اثمرت عن فهم طبيعة هذه العلاقة علي مستوي تحت السطح وتجاوزت هذه الدراسة المشكلة المتعلق بدراسات تحت السطح المتمثلة في عدم توفر البيانات الكافية وكذلك النموذج الناتج من هذه الدراسة ساعدنا علي فهم التوزيع الرسوبي والتركيبي للمتكونات الجلدية.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The deposition of late Ordovician sediments corresponding to Ordovician- Cambrian first order retrogradational sequence set is characterized by 200 m thick glacial sediments, extending from Oman to Spain and from Mauritania to Saudi Arabia (Ghienne, 2011).

Saudi Arabia is considered as a part of the North-Gondwana Platform with Libya, Mauritania, Niger and Algeria. Most of the Middle East and North Africa was subjected to Hirnantian glaciation (Le Heron et al., 2009). The North-Gondwana Platform is considered the proximal ice zone and most of the glaciation features can be found throughout the internal platform. The distal part of the ice zone includes Spain, Morocco, Turkey (Ghienne, 2011).

Sarah Formation is found exposed in central Saudi Arabia and includes glacial and pre-glacial sediments, which considered as paleovalley infill of the late Ordovician age. The Arabian plate underwent two glacial events in two different geologic ages (figure 1-1). The thickness of Sarah Formation in the center of the Arabian plate varies from hundred to several hundred meters of fine to medium grained sandstone with tillite facies of glacial to marine origin.

The Paleozoic glacial and fluvial strata are found well exposed in central Saudi Arabia and equivalent glacial deposits are also recorded at Wajid sandstone group (Sanamah Formation) in south-western Saudi Arabia, northern Saudi Arabia and there is a limited subsurface occurrence in Rub al Khali Basin. Regionally, equivalent glacial deposits are recorded in southern Turkey, Algeria and Mauritania (Moscariello et al., 2009).

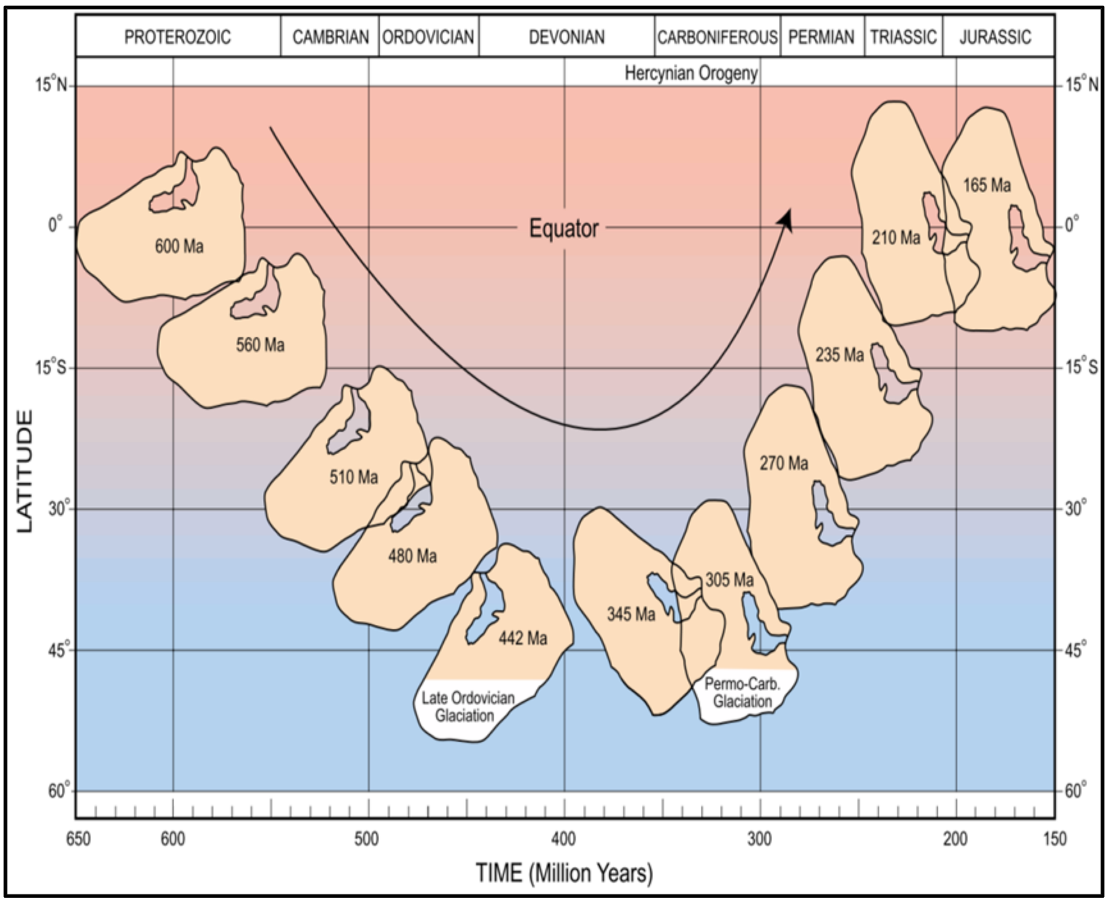

Figure 1.1 Arabian Plate position in the Paleozoic and early Mesozoic. (Konert et al., 2001).

Sarah Formation is considered as one of the important targets for unconventional natural tight sandstone gas resources in Saudi Arabia. Therefore it is important to study its sedimentological and geomechanical properties and fracture pattern, which can all help in understanding and predicting the geomechanical behavior of Sarah Formation in the subsurface. The outcomes of this research are expected to contribute in the assessment of the geomechanical properties and reservoir quality of Sarah Formation units based on outcrop observations and laboratory studies, which helps in understanding the reservoir units of Sarah Formation in the subsurface.

1.2 Study Area

The study area is located in central Saudi Arabia in Al-Qaseem area, where Sarah Formation is well exposed. Sarah Formation is exposed in more than six Paleovalleys, which are deeply incised into Saq Sandstone, Zarqa Formation and Qaseem Formation at Baqa quadrangle (Figure 1-2). The Sarah Formation is considered as tight gas sandstone reservoir with mostly unexplored area of Paleozoic petroleum system (Millson et al., 1996, Schenk et al., 2000). The lithofacies in the outcrop varies form glaciofluvial sandstone packages characterized by large boulders of slumped siltstone and |shale bodies distributed through paleochannels. The top part of the outcrop is characterized by moderately sorted white fluvial sandstone. This heterogeneity has impact on the petrophysical and geomechanical properties of Sarah Formation sequences in the area, and similar effects are expected to take place in Sarah Formation in the subsurface.

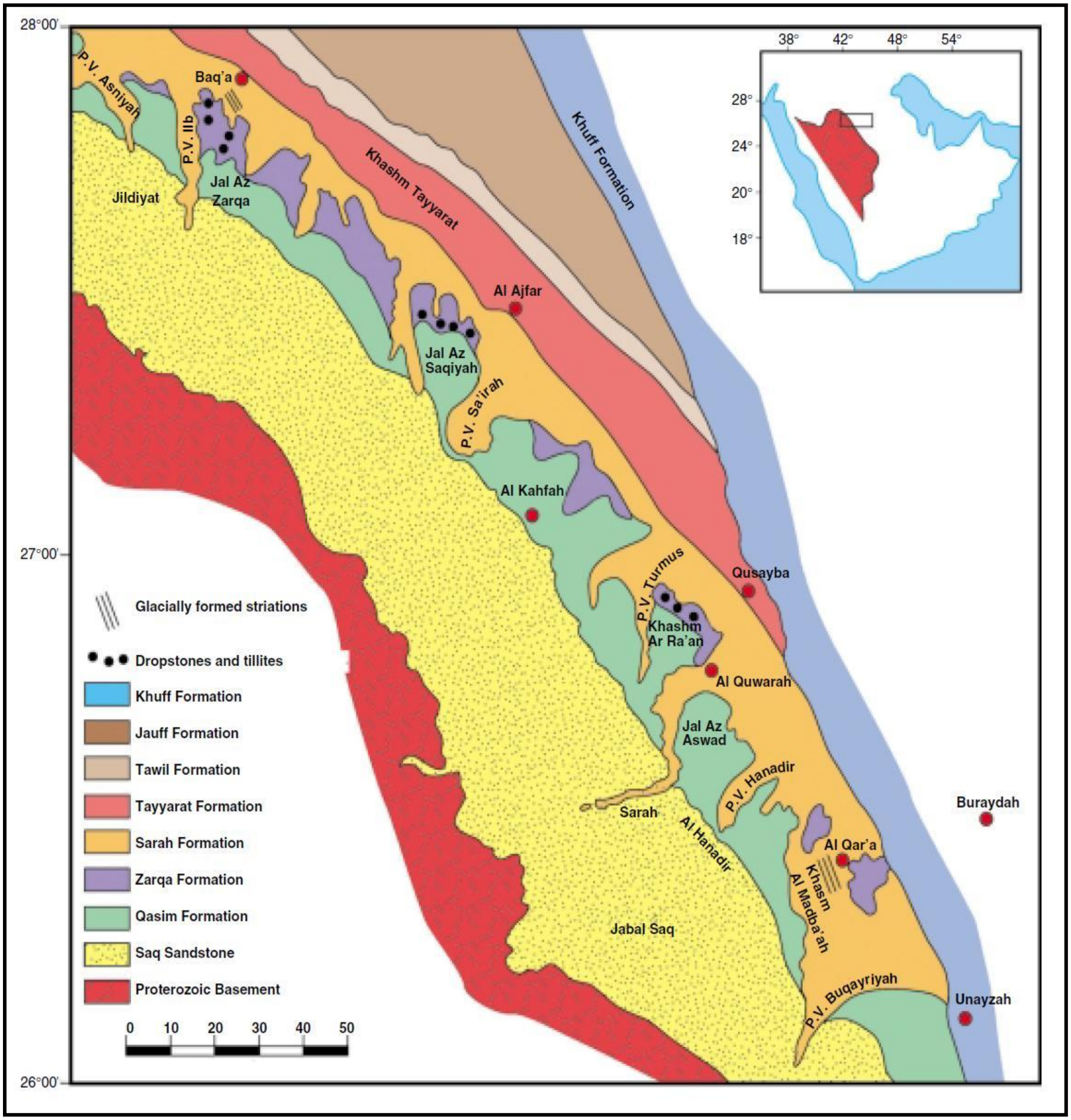

Figure 1.2 Paleovalleys distribution in Al- Qaseem and Baqa area, Saudi Arabia (Senalp and Al-Laboun, 2000).

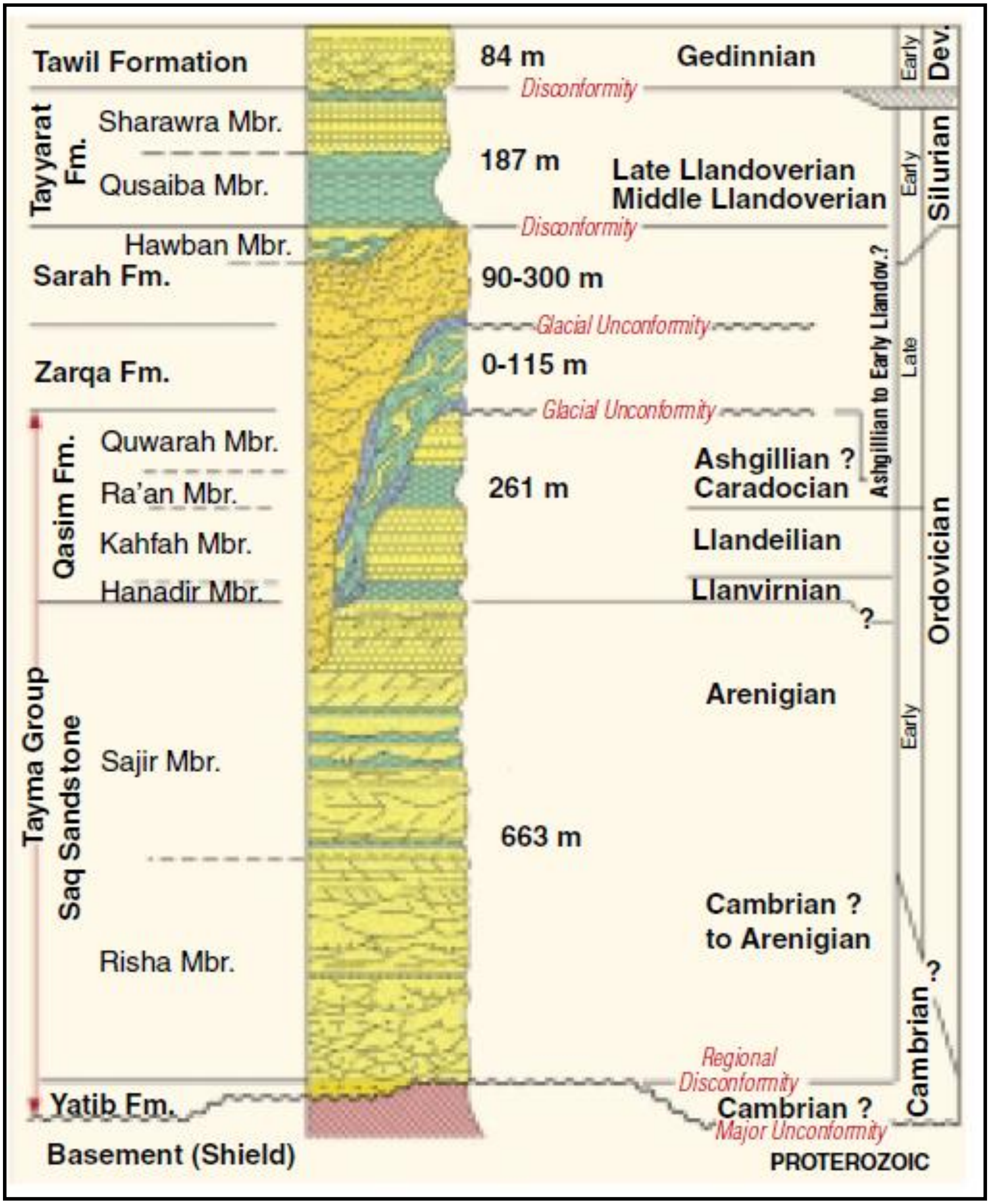

Figure 1.3 The Paleozoic stratigraphy of Central Saudi Arabia including Glacial Sarah Formation (Senalp and Al-Laboun, 2000; after Vaslet, 1989).

1.3 Problem Statement

Many studies on Sarah Formation have taken place but most of them focused on the stratigraphic characteristics of Sarah Formation without touching its geomechanical characteristics. Sarah Formation is considered as tight sandstone reservoir in large unexplored areas in the subsurface.

Tight gas reservoir productivity has increased by understanding the geomechanical nature of the reservoir formations and the relationship between sedimentological and geomechanical properties, the hydraulic fractures in tight reservoirs playing a major role in production process, which may increase the production or decrease the productivity by sealing the natural fractures.

The study of the geomechanical properties of Sarah Formation is very important, as it can help to predict the geomechanical properties in the subsurface and to define the direction of maximum stress, which is the main factor for perfect fracturing mechanism.

The relationship between the lithostratigraphy and geomechanical properties for Sarah Formation is still largely unknown. The study of geomechanical and lithostratigraphical characteristics of Sarah Formation in the outcrop can help us to predict the relationship in the subsurface, which can help in increasing the reservoir productivity.

1.4 Scope and Objective

Sarah Formation is considered a tight sand reservoir in the subsurface; therefore, prediction of its mechanical properties is very important for horizontal drilling and establishing effective hydraulic fracturing. This research aims to study the geomechanical properties and fracture characteristics of Sarah Formation and the relation between geomechanical properties and sedimentological characteristics in the outcrop as a first step to understand this relationship in the subsurface. The goal of this research is to correlate between stratigraphy and mechanical characteristics for Sarah Formation in central Saudi Arabia, and to incorporate the stratigraphic architecture and vertical facies variations information with mechanical characteristics to those facies, which can led to a better understanding of the mechanical behavior of Sarah formation units, and estimate the fracture characteristics and behavior.

The objective of this research is to:

1- Investigate and characterize lithofacies and sedimentological characteristics of Sarah paleovalley at outcrop scale.
2- Investigate the geomechanical and fracture characteristics in Sarah Paleochannel.
3- Investigate the relationship between mechanical units and stacked sedimentary units.
4- Establish the geomechanical model of Sarah formation paleochannel.

1.5 Previous Studies

Sarah Formation was identified by McClure in 1978 as a late Ordovician glaciation event in Saudi Arabia. The palaeovalleys' glaciation and detailed sedimentology were described by Vaslet (1987, 1989, and 1990). Glacio-fluvial, glacio- marine, glacial deposits and glacial unconformity resulted from late Ordovician glaciation and formed deep incised paleovalley (Senalp and Al-Laboun 2000) mapped by Vaslet (1987, 1989, and 1990).

Rock-mechanical studies are used to differentiate between the layers that have different intensities of deformation according to the changes in petrological and petrophysical properties of the rocks (Nelson, 1985). The term Mechanical stratigraphy was first defined by Corbett et al. (1987), it related to layers with different fracture density of the same type of mode of fracturing. This definition describes the mechanical stratigraphy independently in relation to sedimentary units, and the mechanical unit can include one sedimentary bed or more than one bed. Gross (1995) describes the concept of fracture partitioning which results from differences in failure mechanism due to the differences in lithology and grain size distribution.

(Bukhamseen et al., 2010) established a successful fracture simulation model for Sarah tight gas reservoir in Rub Al-Khali Empty Quarter of Saudi Arabia. He studied the geomechanical properties for Sarah Formation in the subsurface under critical conditions in terms of pressure and temperature.

1.6 Literature Review

The concept of tight gas sand was established by U. S Department of Energy in 1978, in a research in producing natural gases from law permeability reservoir as unconventional gas source.

Sarah Formation in Saudi Arabia is considered as a tight gas reservoir in the subsurface

(Al-Mahmoud and Al-Ghamdi, 2010).

Hussain, M., et al., (2006) studied the control of sedimentological parameters distributions on geomechanical parameters in Khafji Member reservoir rock, including the variation of geomechanical attributes (Poisson's ratio, Young's modulus) in relation to grain size distribution. According to their results, no relation found between geomechanical properties and grain size parameters. This contradicts with the proven result that the clean sand with good to moderate sorting shows low Poisson's ratio and Young's modulus, while in fine grained sediments such as lagoonal deposits one finds higher Poisson's ratio and Young's modulus.

Hsieh, et. al., (2008) interpreted how the sedimentological properties such as grain particles, matrix particles, porosity and petrographic parameters have a relation at the macroscopic scale with the sandstone's mechanical behavior. They created a model to simulate sandstone mechanical behavior on the macroscale based on the bounded particle method, which resulted in good simulation capability and prediction power of the macroscopic behavior of sandstone. They also suggested a relationship between particles and lithological parameters to geomechanical parameters on macroscale. (Figure 1.4) illustrates the relation between axial stress and axial strain for simulated and experimental condition and it shows approximate coincidence and consistence. The strain-stress curves in the bounded-particle model for the simulated and experimental cases underwent a sudden drop in resisting stress after the peak of the curve what reflects typically the failure of brittle rocks. (Figure 1.5) describe the relation between uniaxial compressive strength (UCS) and petrographic parameters (GAR) with values of porosity, the experiment explains that for specific porosity value, the uniaxial compressive strength is inversely proportional with the petrographic parameters. The same relation between Young's modulus and petrographic parameters is shown in (Figure 1.6).

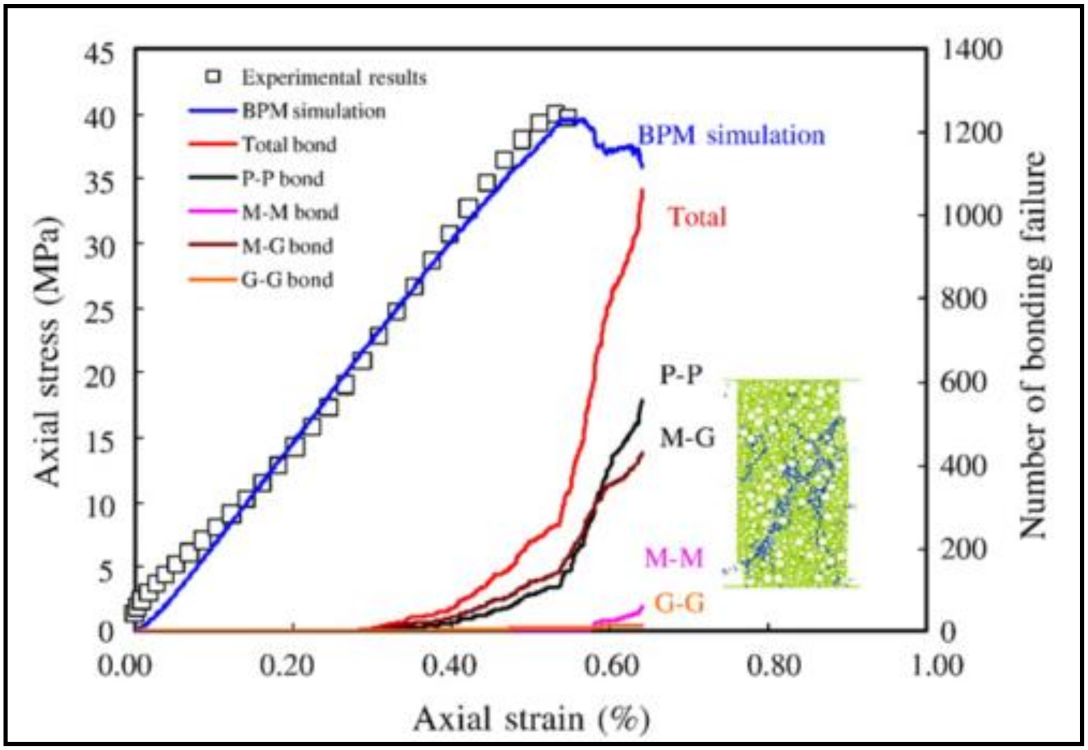

Figure 1.4 Empirical relation between simulated and experimental strain-stress curves at porosity n=20% and petrographic parameter GAR= 35%. (Hsieh, et. al., 2008)

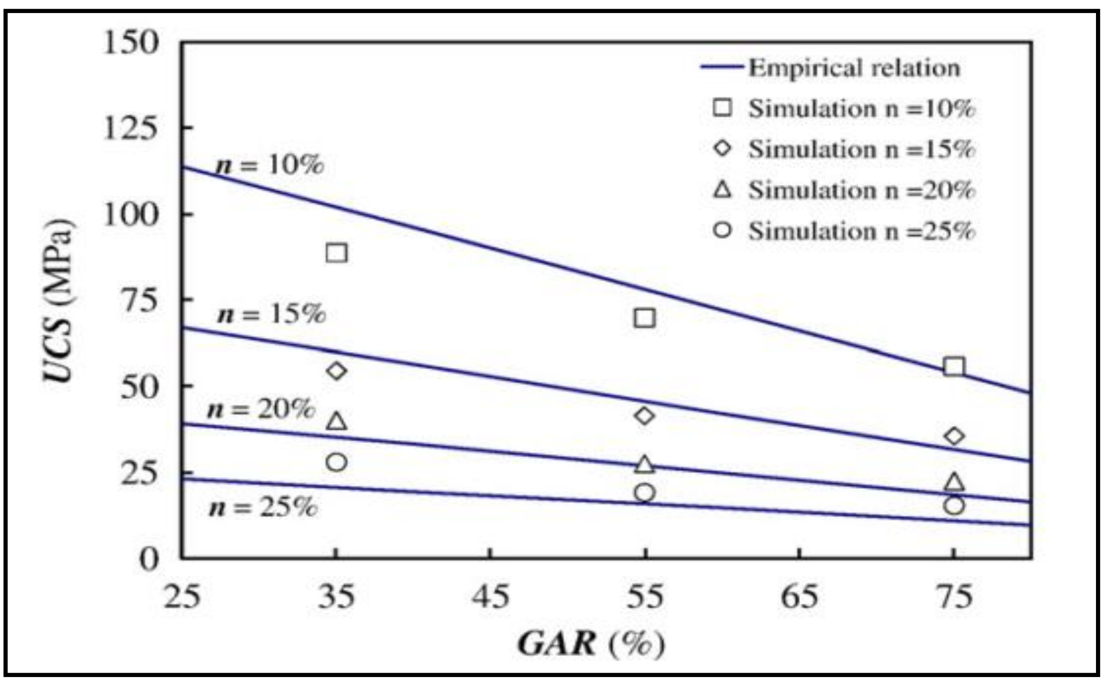

Figure 1.5 Empirical relation between petrographic parameters (GAR) and uniaxial compressive strength.(Hsieh, et. al., 2008)

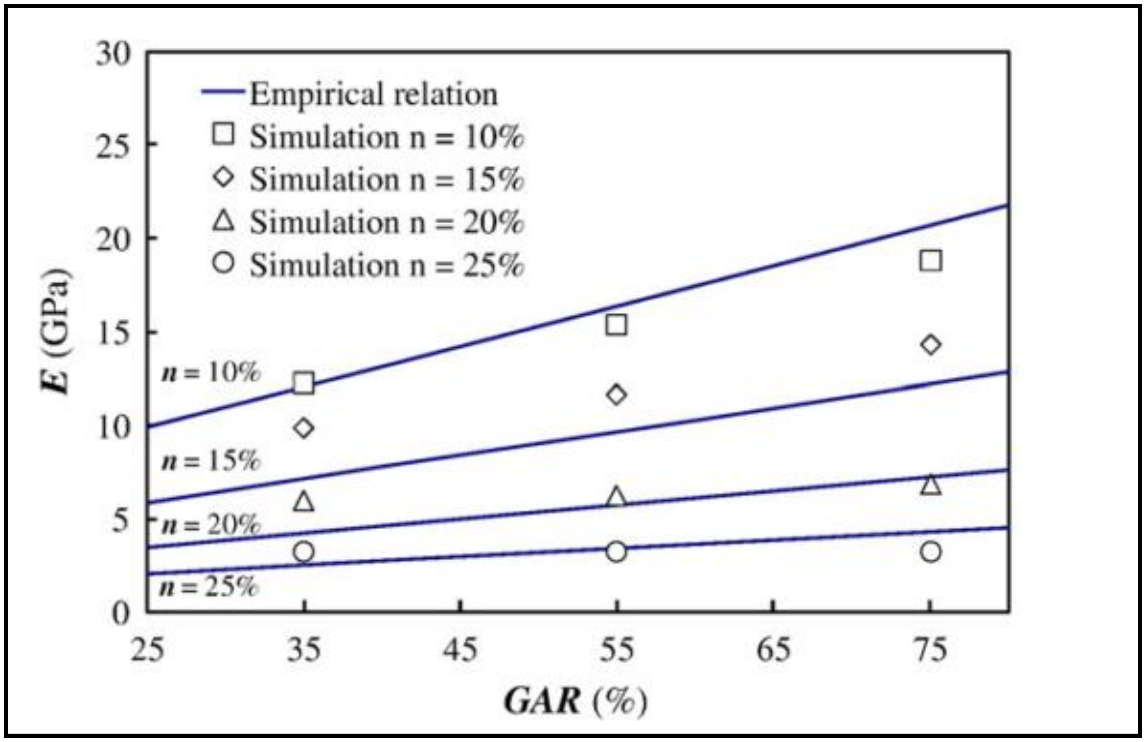

Figure 1.6 Empirical relation between petrographic parameters (GAR) and Young's modules with porosity (n).(Hsieh, et. al., 2008).

Bukhamseen et al., (2010) established a successful fracture simulation model for Sarah tight gas reservoir in Rub Al-Khali Empty Quarter of Saudi Arabia. The challenge in this work had been to simulate tight gas reservoir of Sarah Formation successfully under extremely high pressure and temperature condition at depth between 18,100 ft. to 18,600 ft. approximately. Some geomechanical parameters investigated were the modules and the fracture pattern from the FMI log, which was found ranging between resistive, closed fracture to conductive, open fracture, and four fracture intervals found in Sarah Formation (figure 1-7). This work resulted in the first successful discovery of tight gas in Rub Al-Khali Empty Quarter of Saudi Arabia with low coast and effective timing; hence, the study of mechanical properties of Sarah Formation will add and gives many ideas.

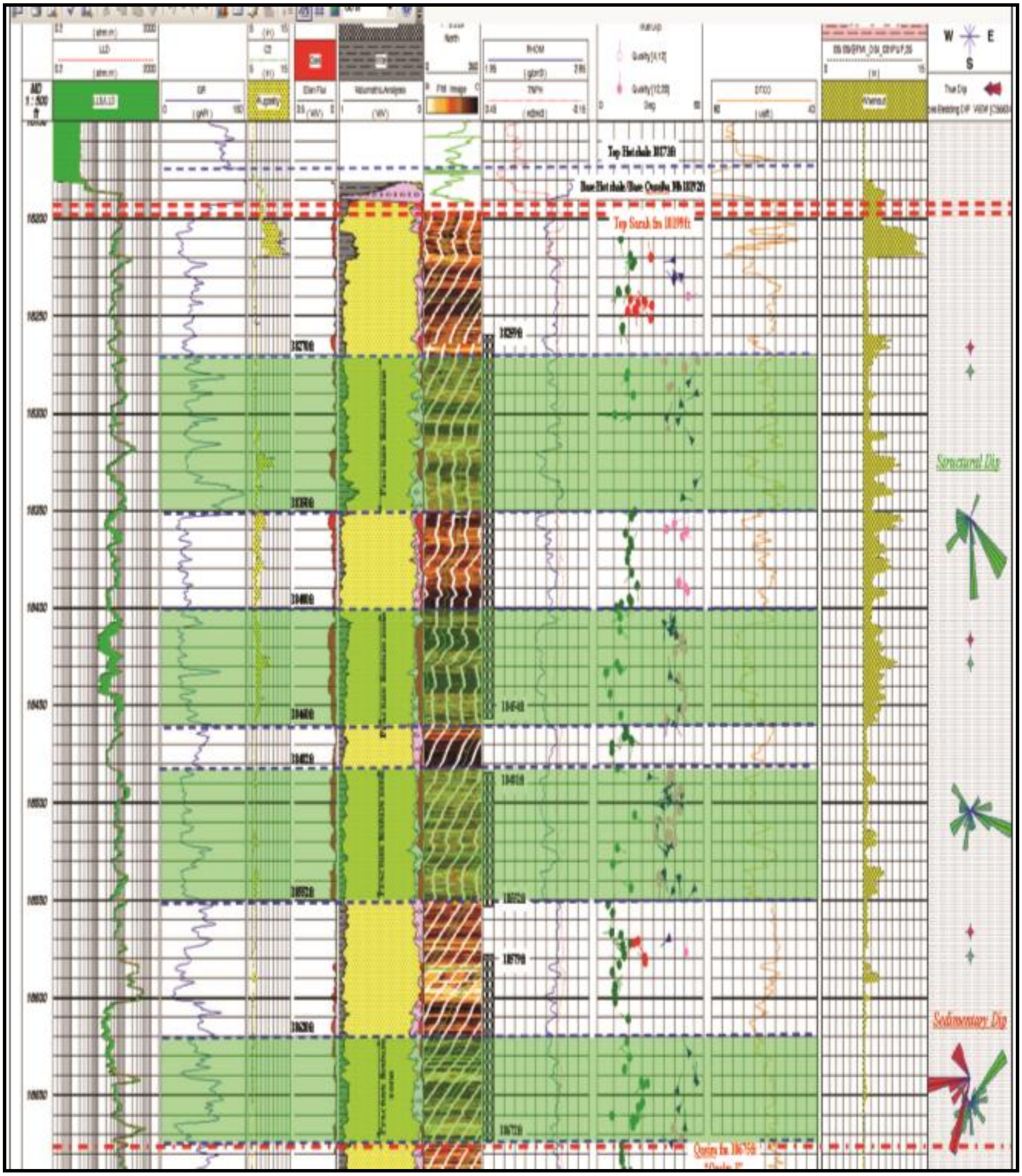

Figure 1.7 Image log for Sarah Formation describing four fracture zones. (Bukhamseen et al., 2010)

The geomechanical properties of Sarah Formation in the subsurface have been studied by linking the geomechanical properties to lithology and study the relation between them.

Since now there is no published work that would examine the geomechanical properties of Sarah Formation in the outcrop.

Al Kharusi, L. (2009) studied the correlation between high-resolution sequence stratigraphy and mechanical stratigraphy for enhanced fracture characteristics prediction in a steep mountain anticline in Wyoming, Middle Mississipian carbonates of St. Louis basin and Paradox basin, at Utah. The mechanical analysis investigated many parameters which including grain density, porosity , velocity measurement and statistical analysis which in turn includes fracture Density/Intensity, fracture spacing ratio, dynamic moduli (Bulk modulus, Young’s modulus, Poisson ratio) and rigidity ratio. After petrophysical analysis, she linked all geomechanical parameters with the high-resolution sequence stratigraphy.

She concluded that, the genetic boundary of higher order sequence acts as mechanical boundary, a mechanical unit can include less or more than one stratigraphic unit and the fracture parameters such as fracture length and spacing are affected by external properties such as internal bedforms and bed thickness but not significantly by lithology, porosity and rock stiffness.

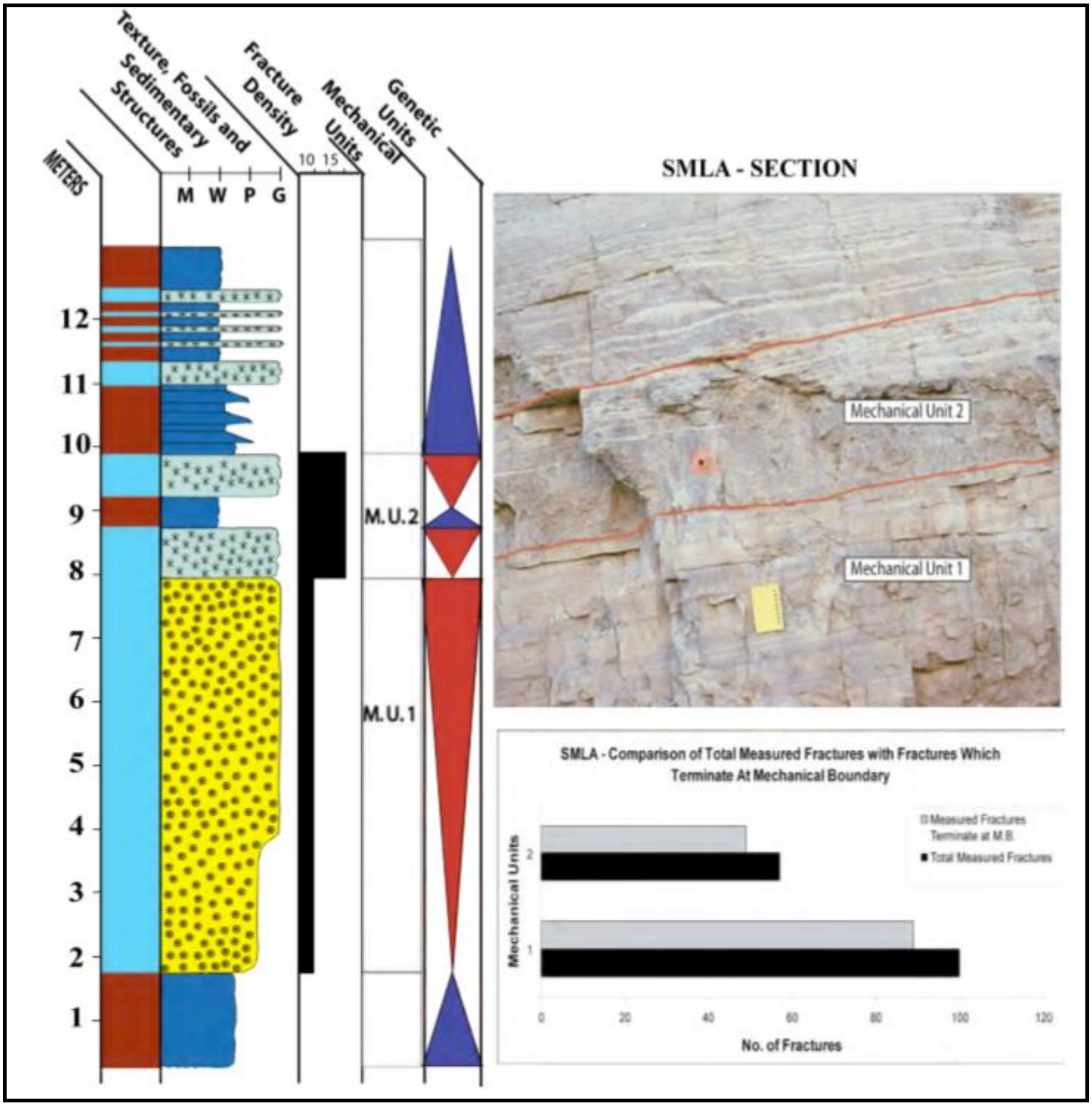

Figure 1.8 Correlation between mechanical units and genetic unit boundaries in the Madison Formation. Al Kharusi, L. (2009).

Ameen, M., et al., (2009) studied the prediction of carbonate mechanical properties of Arab-D Reservoir from wireline logs. They used 400 plugs mainly from Arab-D reservoir unit and tested their mechanical and acoustic properties under increasing triaxial stress. The results indicated that the rock mechanical parameters are mainly related to porosity and related for less degree to texture and minerology. They used S-wave, P-wave velocities with porosity to establish a correlation formula which can be applied for the acoustic log to derive mechanical properties (pseudo-log) (Figure 1.9),-as a predictive tool in reservoir management and development (eg: hydrofracturing).

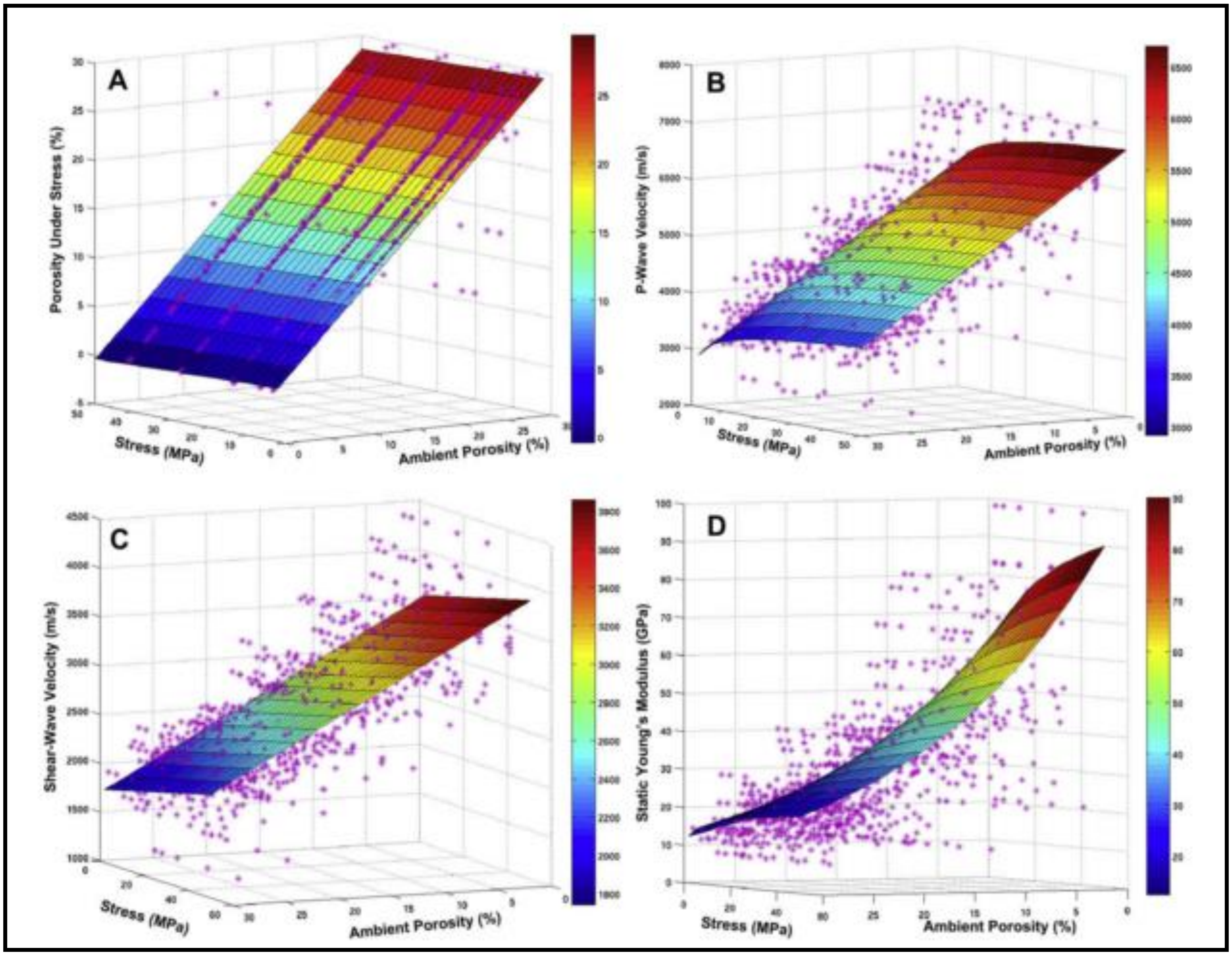

Figure 1.9 Three dimensional plot describing the relation porosity stress space with Porosity V; B. S-wave velocity C. P-wave velocity Vp; Vs; D. Static Young's modulus. (Ameen, M., et al., 2009).

Abdullatif, (2010) studied the geomechanical properties in the outcrop for Rus Formation in Dammam Dome by investigating many mechanical parameters to assessing Rock Mass Rating (RMR) and Quality Index (QI) and he compared this properties for Lower and Middle Rus Formation. He measured many parameters in the outcrop such as discontinuity spacing, orientation, uniaxial compressive strength (point load), stress and joint water reduction factor, condition and orientation in addition to the laboratory work which included porosity, dry density, Schmidt hammer, rebound number, uniaxial compressive strength, Young's modulus, point load index test, permeability, water absorption and Poisson's ratio. He obtained the relationship in (figure 1.10), which shows that the rock quality and rating in Middle Rus are higher than Lower Rus.

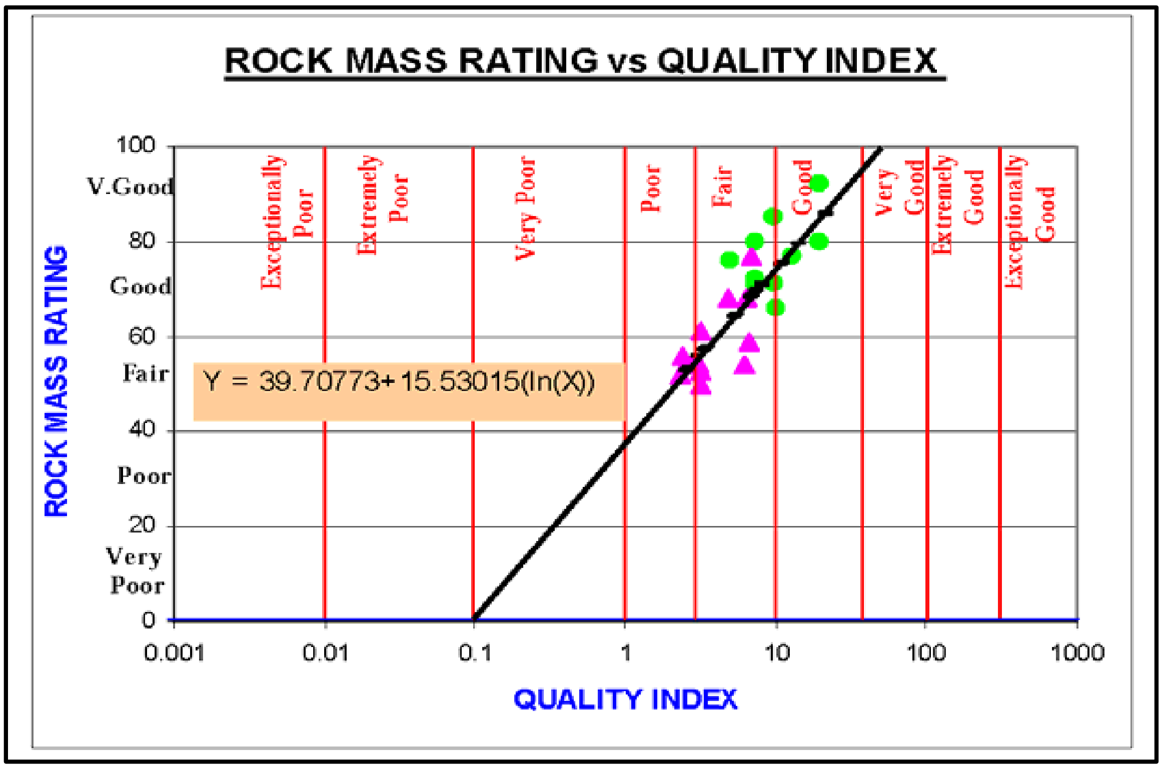

Figure 1.10 Relationship between rock mass rating (RMR) and quality (Q) for middle (circles) and lower Rus (triangles) Formation (Abdullatif, 2010).

Petrie et al., (2012) studied the lithology and fractures of seals, which affected their hydrogeologic and mechanical properties in S-E Utah. They investigated the fracture development and mechanical stratigraphy to estimate the distribution and nature of fluid flow in different seal lithologies. To achieve the goals they measured the sedimentological characteristics such as rock description, mineralogical composition, bed thickness and lithological changes. Furthermore, they scanned the fracture distribution and investigated geomechanical properties using Schmidt hammer and measuring compressive strength. They concluded that the fracture density and morphology varies with changes in mechanical properties and in lithology in m and cm scale. Understanding natural fractures in different structural settings and different seal types will enhance our understanding of hydraulic fracturing. The lithological load (up to over-pressure) during burial would result in tensile failure, which in turn will affect the seal integrity.

Alikarami,R. et al., (2013) studied the geostatistical relationships between petrophysical and mechanical properties of deformed sandstone of Entrada and Navago sandstone in Utah. They studied the relationship between different petrophysical parameters and geomechanical parameters such as the relation between Schmidt hammer values and Tiny-perm II measurements, uniaxial compressive strength versus permeability and Young's modulus versus permeability in a deformed zone. The statistical results showed correlation relationships between parameters but depending on the degree of calcite cementation to quartz sandstone, and related to the deformational processes (Figure 1.12).

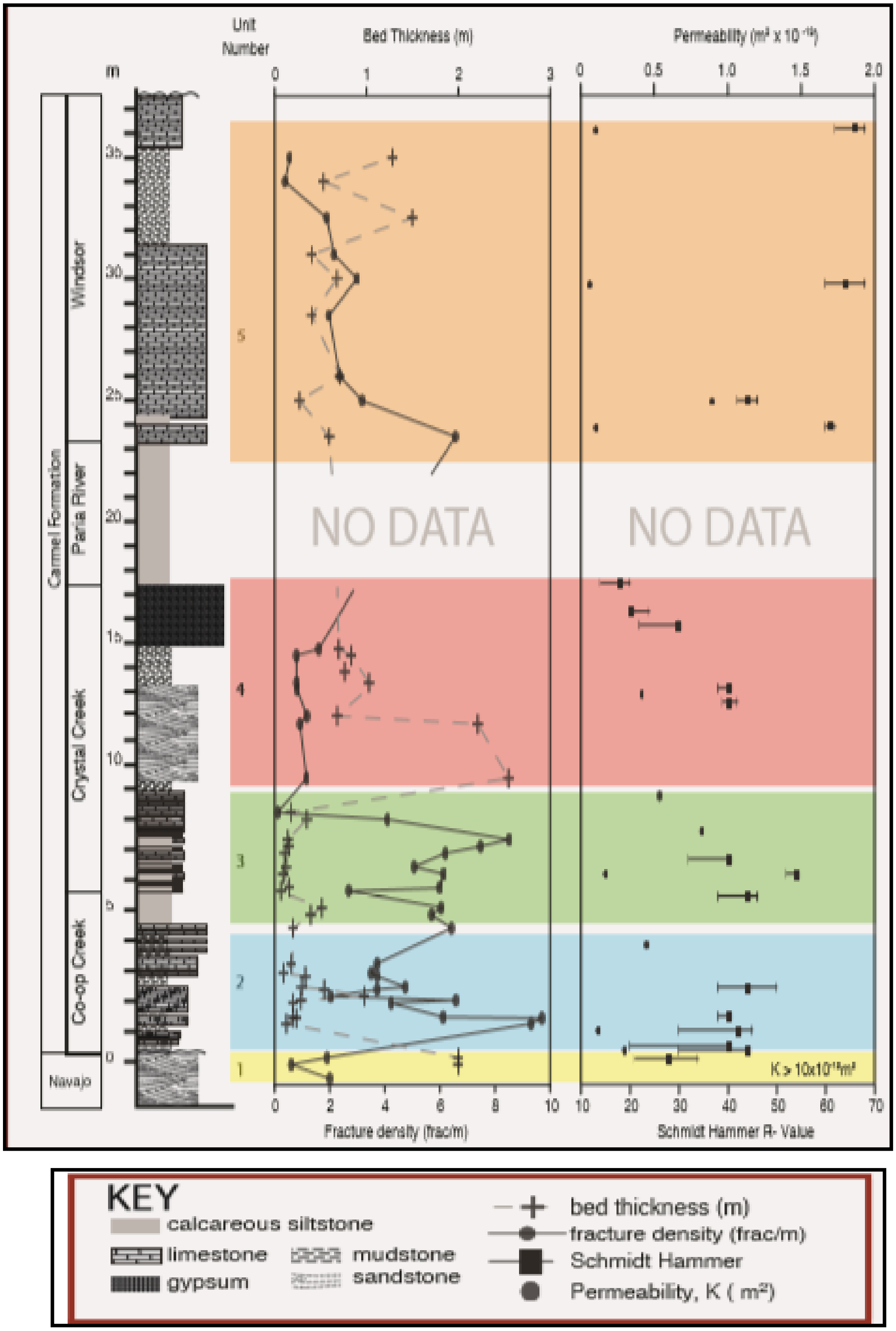

Figure 1.11 Carmel Formation out-crop mechanical stratigraphy (Petrie et al., 2012).

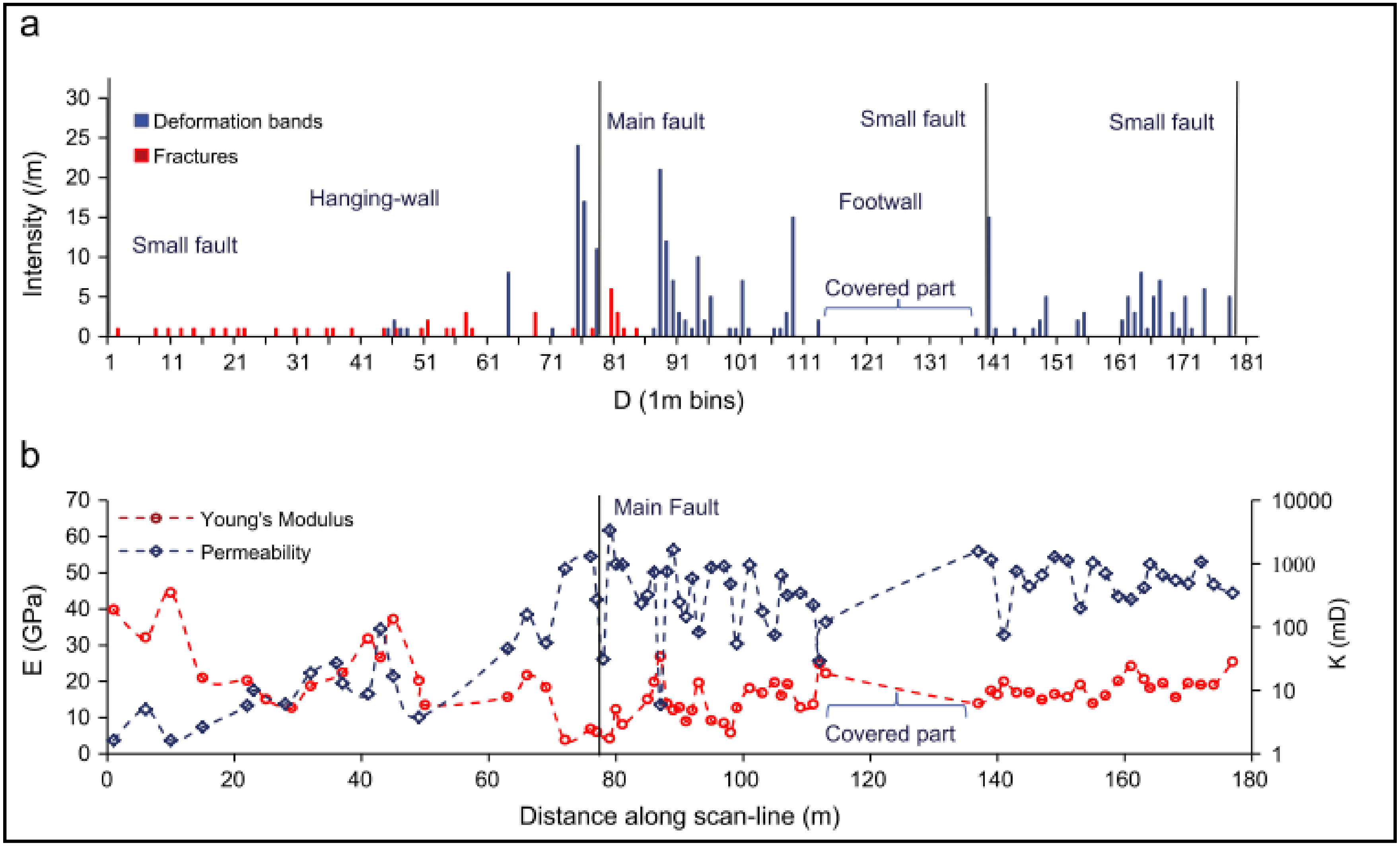

Figure 1.12 Deformation elements intensity (b) Young's modulus vs. permeability along scan line. At Cache valley (Alikarami,R. et al., 2013).

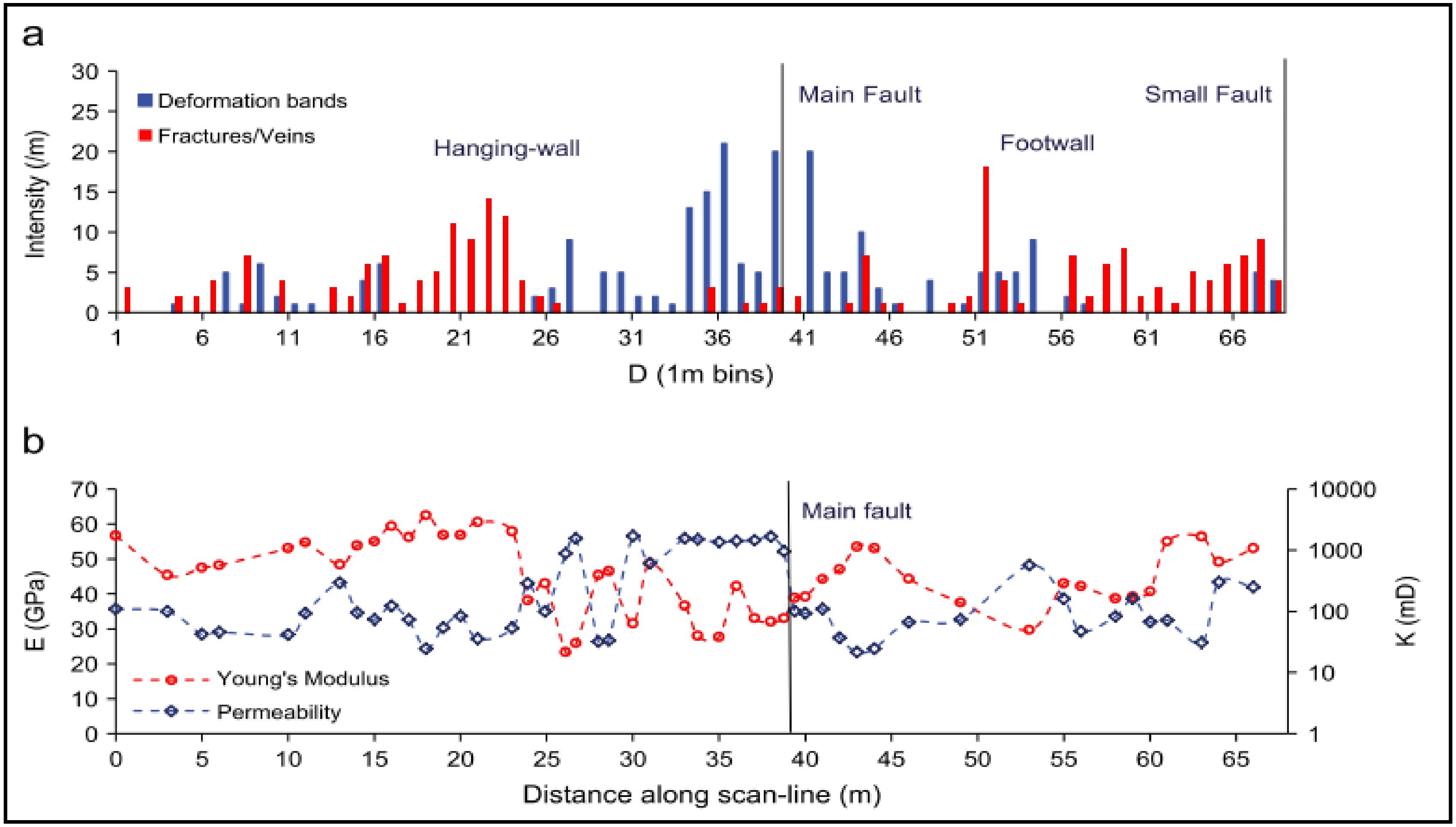

Figure 1.13 Deformation elements intensity (b) Young's modulus vs. permeability along scan line. At San-Rafeal Swell (Alikarami,R. et.al., 2013).

The conclusion of field measurements and statistics indicated concordance of both elasticity/strength and permeability in the damage zone in terms of type and density of deformation band and fractures.

Dewers, et al. (2014) studied the geomechanical behavior of Iowa shelf sandstone lithofacies, which is considered as a target for CO2 waste injection. They defined the geomechanical properties for Mount Simon lithofacies experimentally, which include elastic moduli using unload-reload cycles, stress and strain. Experimentally they proved that the upper units of Mont Simon lithofacies show higher shear stress than the weaker and plastically deformed lower lithofacies of Mount Simon.

They concluded that there are three lithofacies, with different geomechanical properties, and interpreted this variation to influence of intergranular cement, grain size and weaker framework grains.

They used sonic velocities from wireline log to calculate the dynamic moduli for the lithofacies and ~~he~~ found linear relationship between bulk moduli, dynamic and static shear of lithofacies. They recommended to use the dynamic moduli to model Mount Simon storage, including its compressibility and storability.

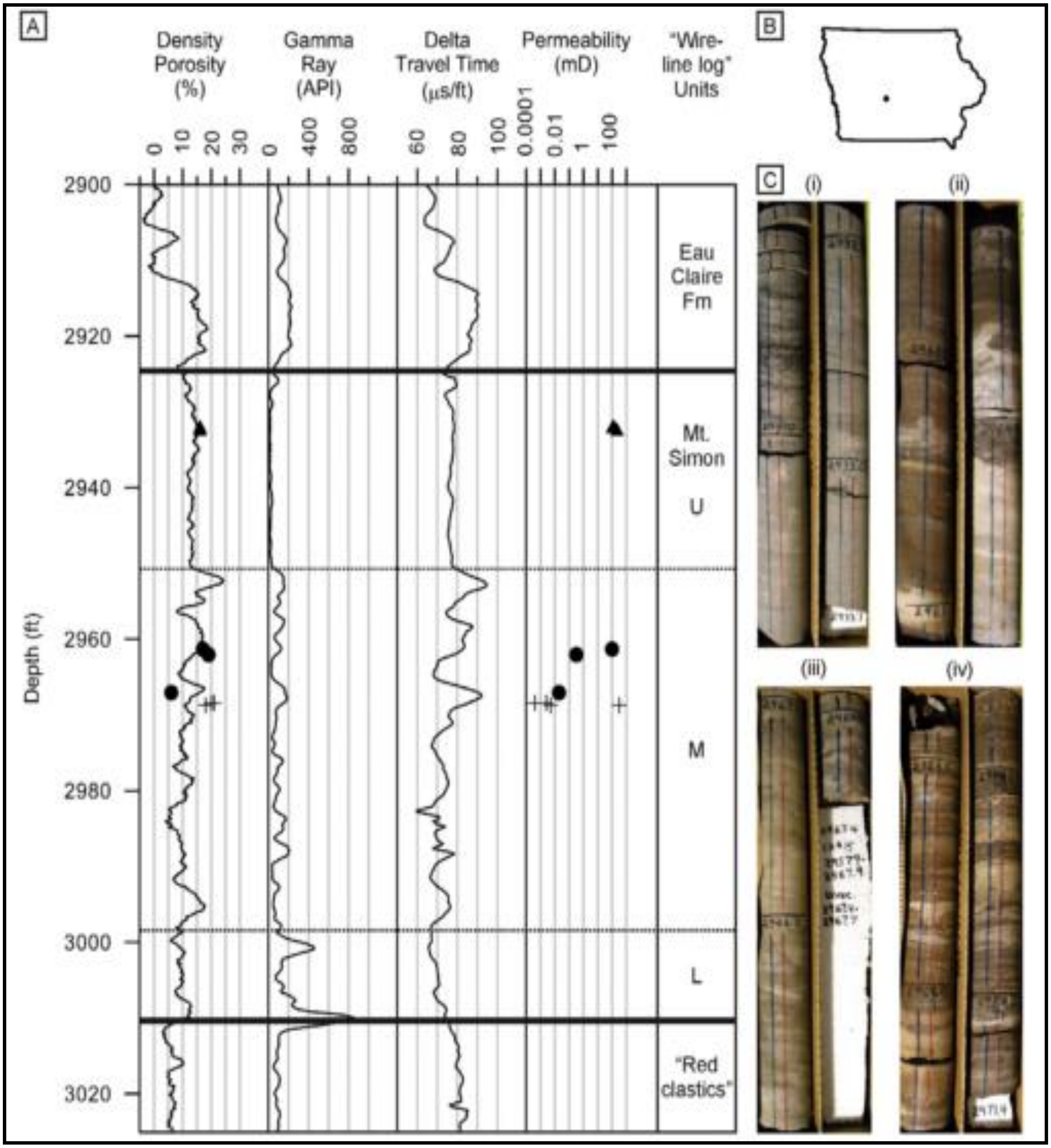

Figure 1.14 (A) Laboratory-measured permeability, porosity and wire line logs, (c) images from core showing lithofacies. (Dewers, et. al. 2014).

Lateral and axial strain vs. Axial stress in MPa.

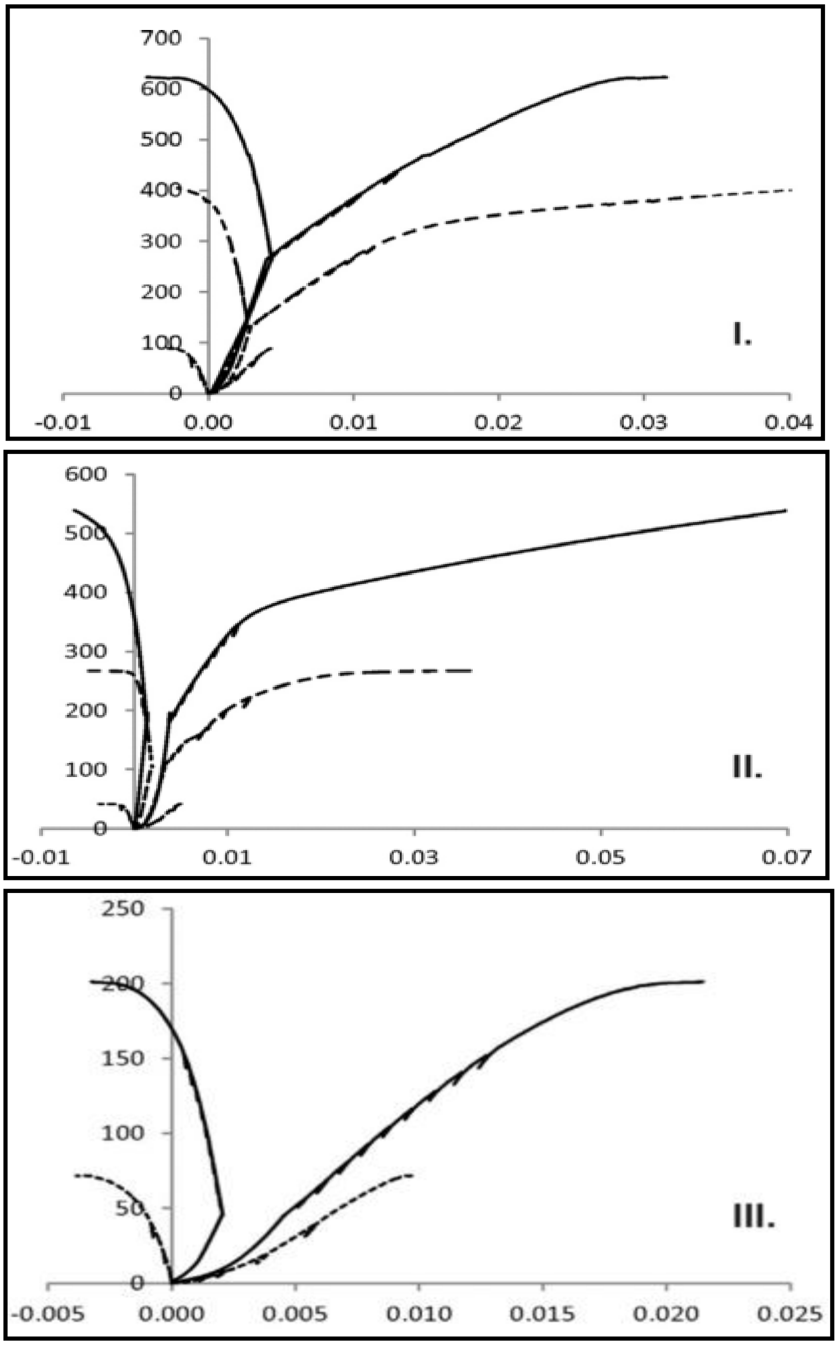

Figure 1.15 Summary of geomechanical tests of three lithofacies (lower, middle, top) axial and lateral (right to left respectively) strain for triaxial and unconfined-compressive stress. (Dewers, et al. 2014)

CHAPTER 2

Methodology

2.1 Introduction

My study of the mechanical properties of Sarah Formation started by field investigation in Central Saudi Arabia, Qaseem Formation, where Sarah Formation crops out in Rawd Al-Jawa area. Sedimentological and geomechanical studies were conducted on the outcrops and all required data were collected. This step was followed by laboratory analysis for the collected samples. The obtained data included thin sections for selected lithofacies, porosity and permeability measurements, spectral gamma ray, Lidar imaging, point load test, uniaxial compressive strength test, Schmidt hammer test and velocity measurements. This step was followed by analyzing the data collected from the field and the lab, including cross plots describing the relationships between sedimentological and geomechanical tests, fracture characteristics, sedimentological and geomechanical unit classification based on the analyzed data.

2.2 Field Investigation

The field investigation conducted in central Saudi Arabia, Qaseem Area, Rawd Al-Jawa paleo-valley, where the glacial Sarah Formation cropped out through the road cut oriented east west direction with. The section had been selected carefully to describe the vertical and horizontal heterogeneity of the formation. The fieldwork started with sedimentological description of selected vertical sections, fracture studies and geomechanical studies on the outcrop. Then Lidar imaging was conducted for the outcrop for fracture and additional office analysis with photo mosaic. The following chart describes the steps of the study.

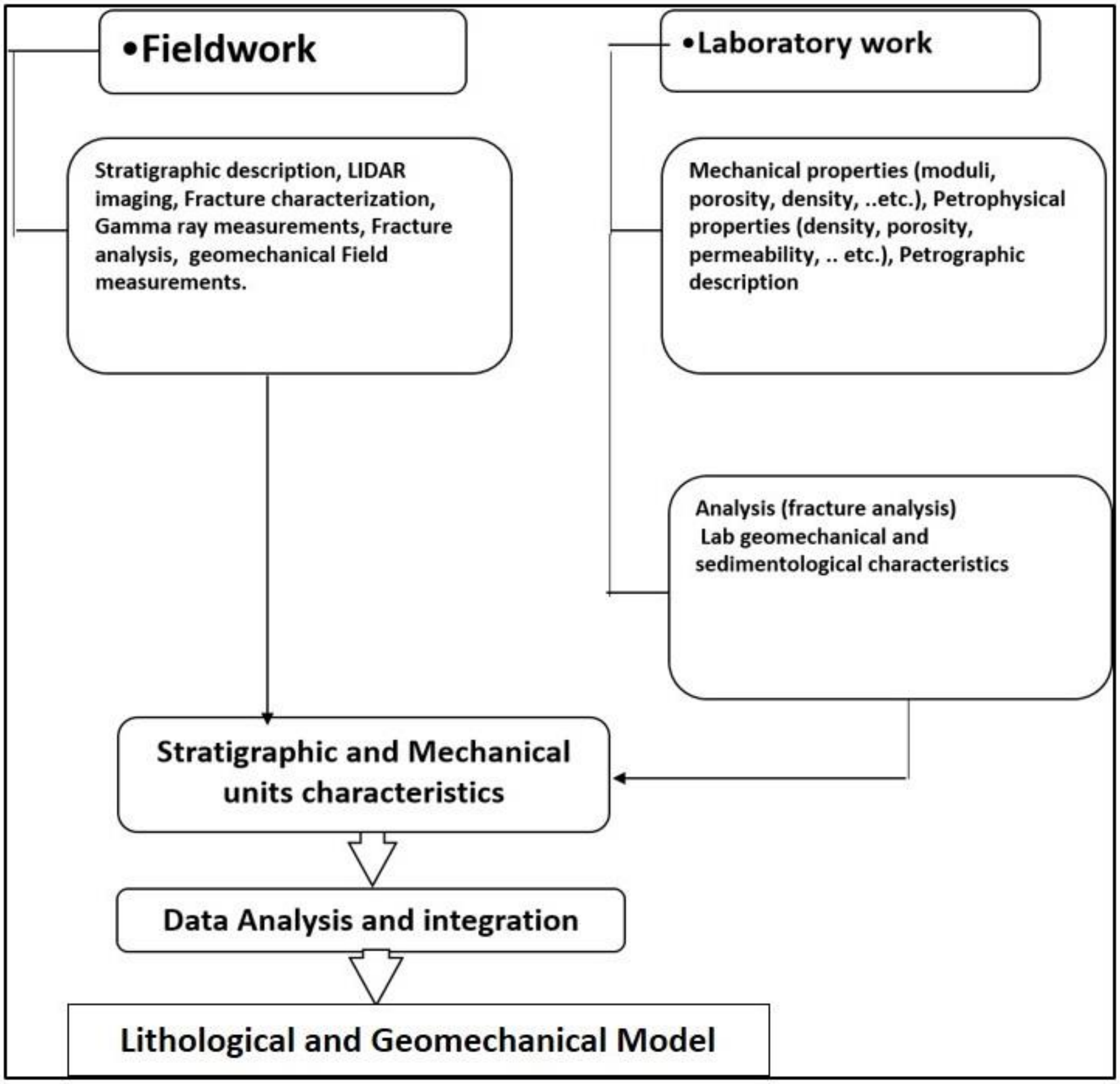

Figure 2.1 Flow chart describing the approach and methods of the study.

2.2.1 Schmidt Hummer

Science the sixties Schmidt Hammer has been used as a non-destructive index test in rock mechanics, which gives quick estimation of rock hardness and strength (Miller, 1965) and is characterized by its rapidity, portability, and simplicity.

The work with Schmidt hammer starts after releasing the pistol perpendicular to the surface and giving impact energy to the rock, which in turn is transmitted as sound and heat and part of it is absorbed. The remaining energy causes the rebound of the piston. A greater rebound results from a harder surface, which in turn gives shorter depth penetration. The rebound value is estimated from the ratio between the travel distances by pistol to the original extension.

There are two hammer types, L and N type, the difference is related to the impact energy of the two types (0.735 and 2.207 Nm).

Many scientist described the relation of the index reading between the two types of hammer, related the correlation to the type of the rocks, such as the linear relationship of carbonates by Sabatakakis et al (1993) and they proved the correlation between Schmidt hammer, compressive strength and Young's modulus to the lithofacies.

Figure 2.2 Schmidt hammer kept perpendicularly to the surface.

2.2.2 Spectral Gamma Ray Response

Gamma ray technique measures the natural gamma ray from the outcrop, and it is also used in boreholes. There~~s~~ are two types of gamma ray logs, those that record individual spectral bands from the gamma ray emission and those that measure the total gamma ray counts that is all gamma rays emmitted from the rock~~s~~. The spectral gamma ray measures emissions from the Thorium (Th), Potassium (K) and Uranium (U) decay series that occur in the measured rocks. The presence of Uranium in the measured gamma ray response indicates high organic matter content, whereas the presence of K and Th is good indicator for feldspars in the silicicalstic rocks.

2.2.3 Lidar (Light Detection and Ranging)

Using the time lapse between light pulsees emitted to the outcrop surface and these pulses being reflected and measured by the reciever one can generate 2D and 3D images with high resolution. In addition the pulse source calculates precisely the angle of emitted light, which accurately describes the spatial position of surface points. In such a way, a huge amount of XYZ coordinates are received and calculated which are known as a cloud of points. (Grant, 2011).Using of Lidar has the advantage to do the 2D and 3D fracture characterization in the office or laboratory carefuly and precisely with the ability to calculate the strike and dip. Lidar is working as a photographer's camera~~s~~ but it takes time depending on the resloution of the results (Bellian, J., et al., 2005).

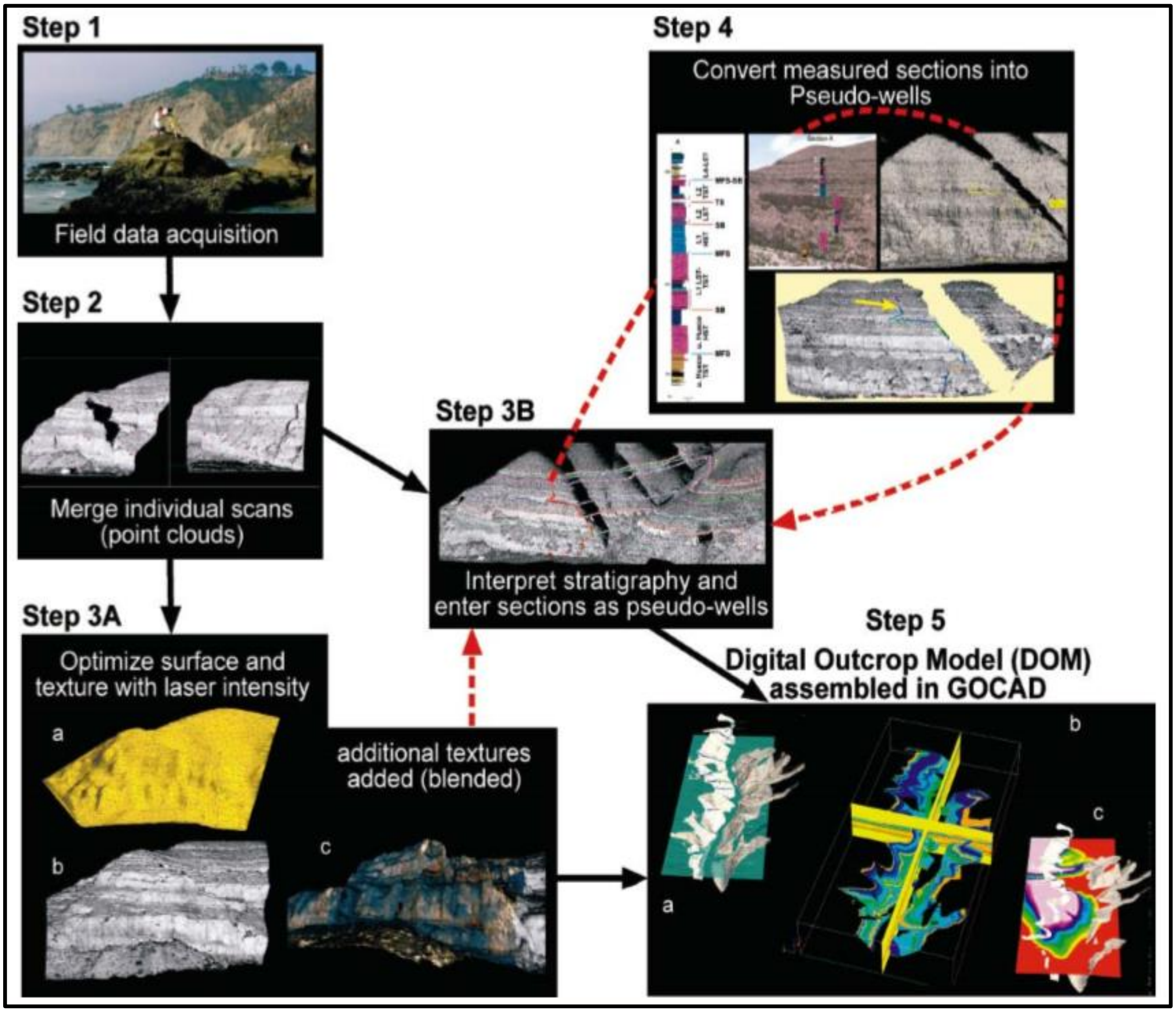

Figure 2.3 Lidar work flow. (Bellian, J., et al., 2005)

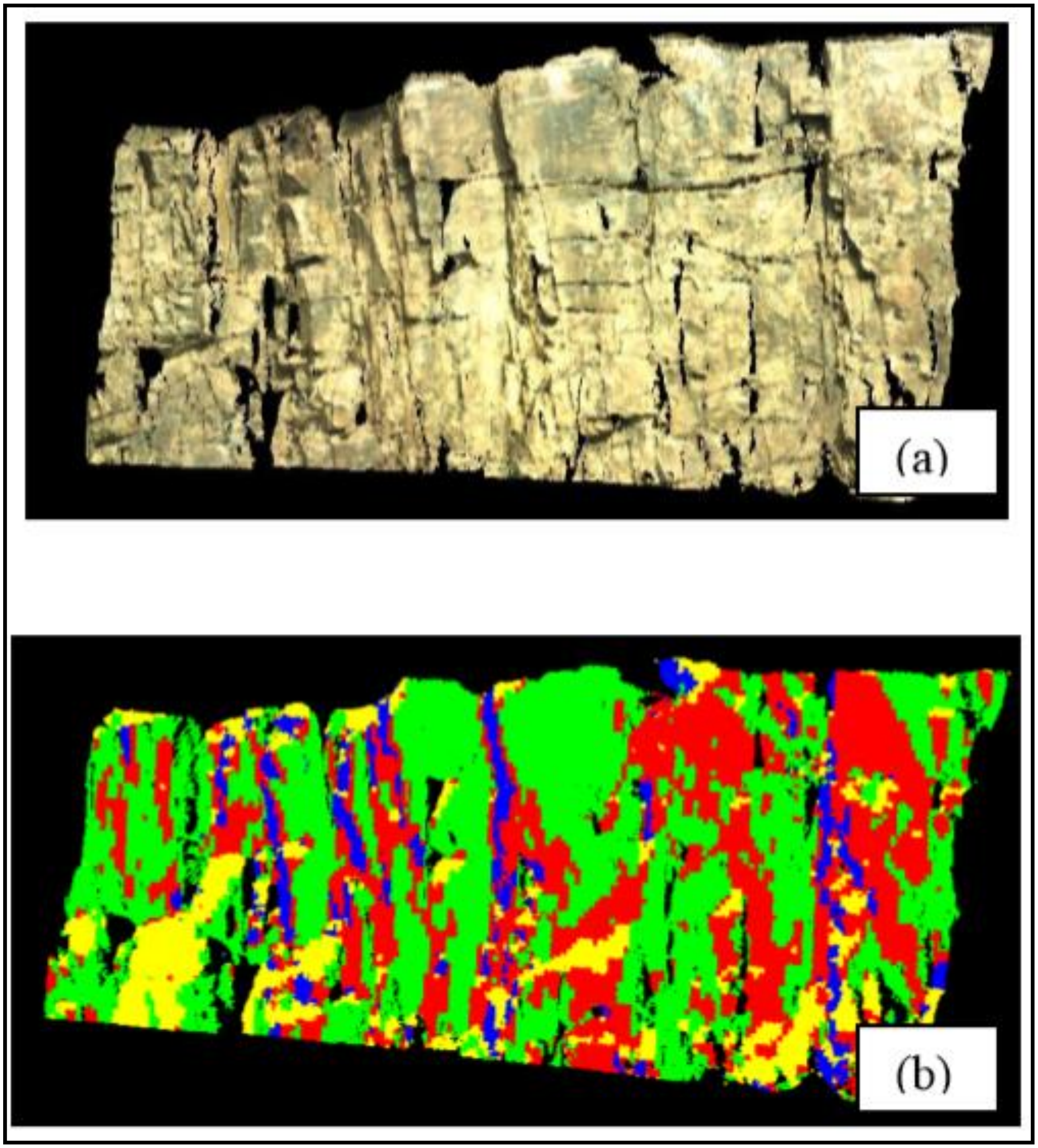

Figure 2.4 Fracture estimation and measurements using Lidar. (Grant, 2011).

2.3 Laboratory Analysis

2.3.1 Uniaxial Compressive Strength (UCS)

Uniaxial compressive strength is a test that measures the maximum load an intact rock sample can be subjected to until failure occurs in unconfined compression. This test reflects the rock's ability to withstand different stress conditions. To get consistent results out of a uniaxial compressive test, many factors in the test procedure must be checked carefully such as length of the sample and smoothness of the sample ends.

According to the International Society of Rock Mechanics (ISRM), the method of UCS determination should agree with that published by (Brown, 1981) who described the standard for some important factors such as length and diameter of the samples. The core length must be close to 152.5 mm and the core diameter must be close to 61 mm to keep the ratio between diameter to length about 2.5:1.

Hawkes and Mellor (1970) tested the change and the variation of the core sample length and diameter and they concluded that the ratio 2.0:1 is the minimum acceptable ratio between length and the diameter under natural condition.

2.3.2 Point Load Index

Point load index is used to test the sample until failure state through applying a concentrated load through a pair of conical, spherically truncated platens which were developed by Broch and Franklin, (1972). This test measures the maximum load applied to the sample until failure by the conical platens along the tension cracks, which is parallel to the loading direction (Goodman, 1980). The failure points are recorded as point load index (Is). According to the standard procedure of point load test suggested by ISRM

(Brown, 1981) the diameter to the total length ratio of the specimen must be greater than 1.0, the distance between the end points in the instrument must be at least 0.5 times the core diameter, and the load must be increased progressively so the failure occurs within 10-60 seconds. Different shapes can be tested including irregular lumps, cylindrical, circular specimens and failure is achieved after 10-60 seconds.

The PLS index is estimated as:

$Is\ (50) = F\ P \backslash De^2$

Where: Is= corrected PLS index. F= the size correction factor, P= the peak load,

De= Diameter of sample, The corrected size index value is measured at D= 50 mm.,

Figure 2.5 Conventional point-load index tool.

2.3.3 Sonic Velocity

The sonic velocity instrument measures the travel time taken by shear wave (Vs) or compressional wave (Vp) to pass through the sample and relates these times to the length of the sample. The Poisson's ratio describe traverse or lateral strain that occur with elongation and axial contraction. The modules of elasticity (E) or the Young's modulus is a proportionality constant that relates strain and stress. If the density of the sample is known, the elastic moduli can be calculated from S-wave and P-wave velocities. The elastic constants (Poisson's ratio and Young's modulus) are measured using static and dynamic methods through calculating vertical stress, vertical strain, and horizontal strain from unconfined compressive strength testing to calculate Poisson's ratio and Young's modulus, or from dynamic moduli which depend on ultrasonic wave velocity tests measuring V_p and Vs.

To calculate the velocity in a cylindrical specimen the test starts with measuring the sample length. An ultrasonic instrument generates pulses from transmitter and received by receiver at the two ends of the sample, the travel time of the pulse is measured, and to calculate the velocity we divide~~d~~ the length of the sample by the travel time ISRM, (1978).

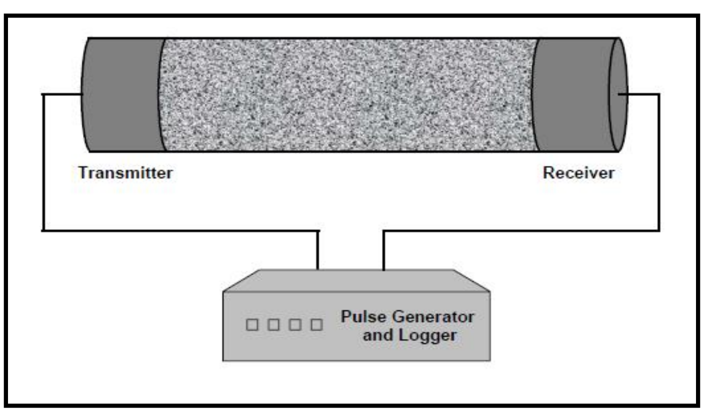

Figure 2.6 Sketch of ultrasonic wave velocity instrument (ASTM, 2006).

2.3.4 Porosity and Permeability

The permeability and porosity measurements were conducted for core plugs representing the lithofacies to detect the heterogeneity within the lithofacies and to determine the relation between porosity, permeability and mechanical tests through cross plots and data analysis. This helps to describe the reservoir quality and heterogeneity in terms of geomechanical and sedimentological properties.

The porosity measurements were conducted by TPI-219 helium-porosimeter using the core plugs of the lithofacies and the standard procedure followed, which required exact readings for the weight, length and diameter of the plugs. (Figure 2-7).The permeability measurements were conducted using TKA-209 gas-permeameter for the same plugs (Figure 2.8).

Figure 2.7 The TKA-209 gas-permeameter

Figure 2.8 The TPI-219 helium-porosimeter

CHAPTER 3

Field Sedimentological Investigation

3.1 Introduction

The field investigation was conducted to collect the required data to describe the lithostratigraphical and geomechanical characteristics for Sarah Formation. The studied outcrop had been selected carefully in Rawd Al-Jawa paleovalley to include the largest number of lithofacies representative for Sarah Formation. The sedimentological and geomechanical tests were conducted on four vertical sections selected carefully to represent lithofacies changes and reflect the reservoir heterogeneity in terms of geomechanical and sedimentological properties. The sampling technique for the vertical section was the same for the four sections. The vertical distance was kept 30 to 40 cm between the samples, which allowed to take representative samples for the lithofacies.

This chapter describes the sedimentological characteristics and features and vertical section descriptions.

3.2 Rawd Al-jawa Paleovalley

Rawd Al-Jawa Paleovalley, located north of Al-Bukayriyah paleovalley, is oriented to northeast direction. The study area (figure 3.1) is located along the road cut which is striking east west and north south directions. The selected vertical stratigraphic section is located at N 26 33.708, E 43 35.758 (section 1), N 26 33.706,E 43 35.768 (section 2) along the south wall of the outcrop. Section 3 and section 4 are located along the north wall of the outcrop. The sections selected are vertical to the paleocurrent direction to show vertical changes of lithofacies (Figure 3-2). The photograph below describes the south wall of the outcrop where section 1 and section 2 are located. The general morphology of the outcrop reflects clear glacial environment with a large boulder of diamictite texture. In addition, the slumped mudstone reflects the glacio-tectonics along the paleovalley.

(Figure 3-2) The photograph shows the north wall of the road cut where section 3 and section 4 are located with clear vertical and horizontal lithological variation.

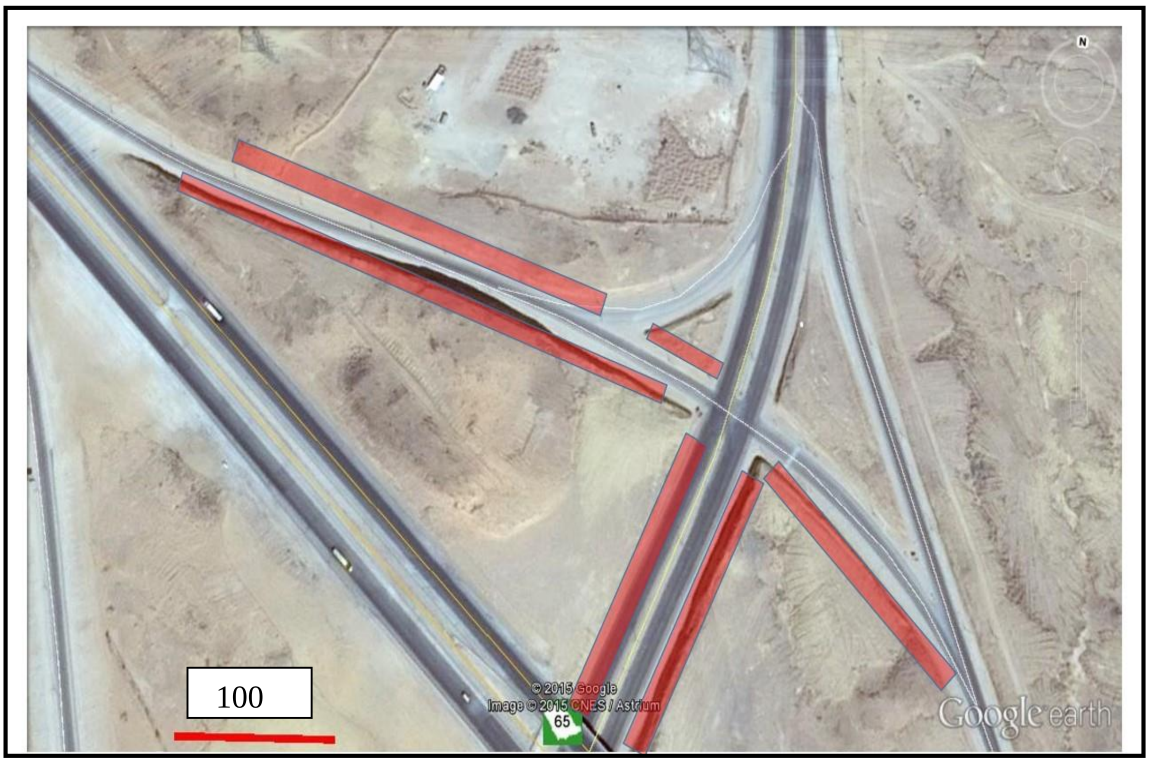

Figure 3.1 Photograph for location of the study area (Sarah paleovalley).

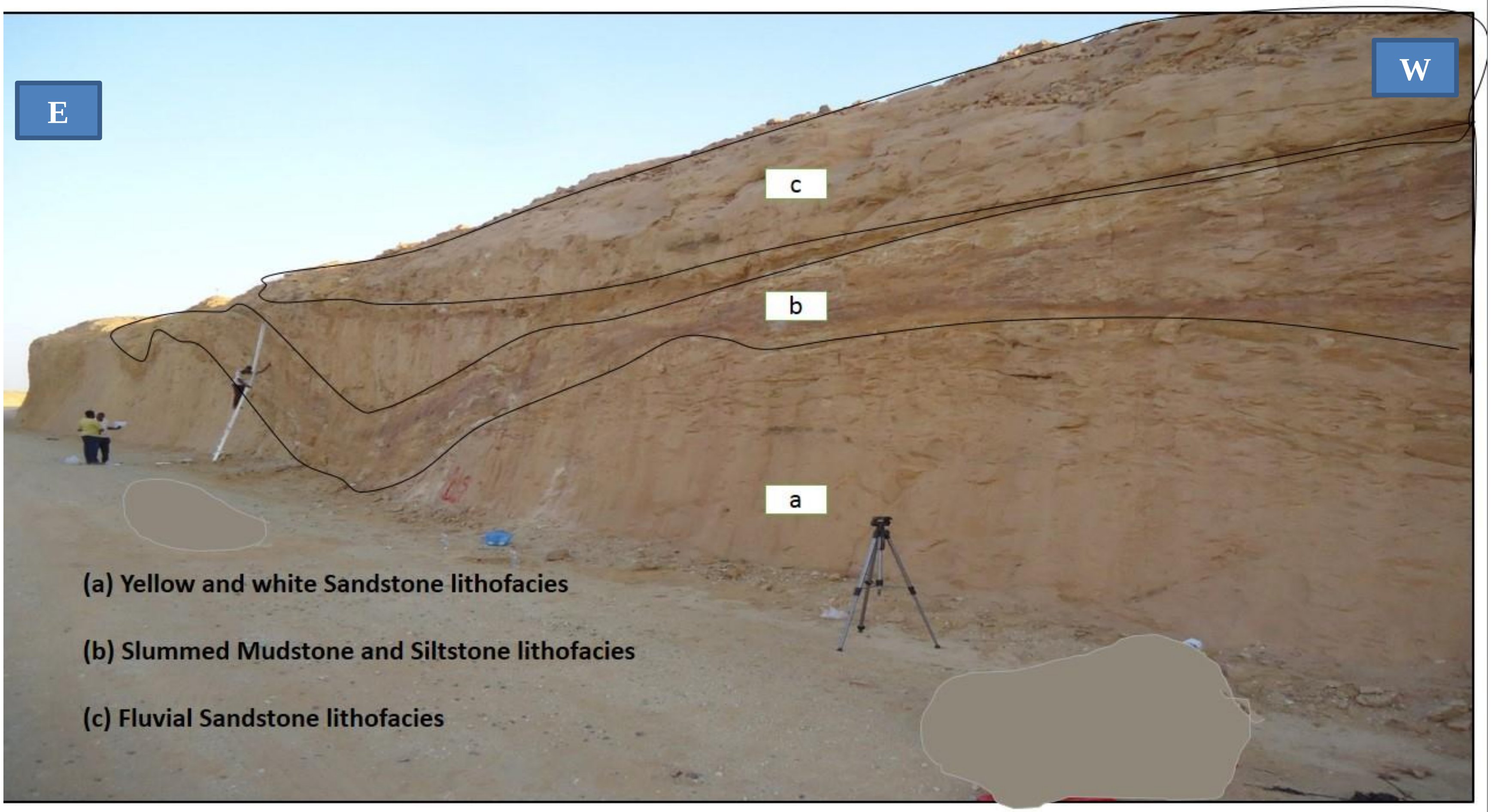

Figure 3.2 Photograph of the south wall of the outcrop at Sarah paleovalley described slumped siltstone and mudstone lithofacies topped by fluvial sandstone and glacial deposits lithofacies

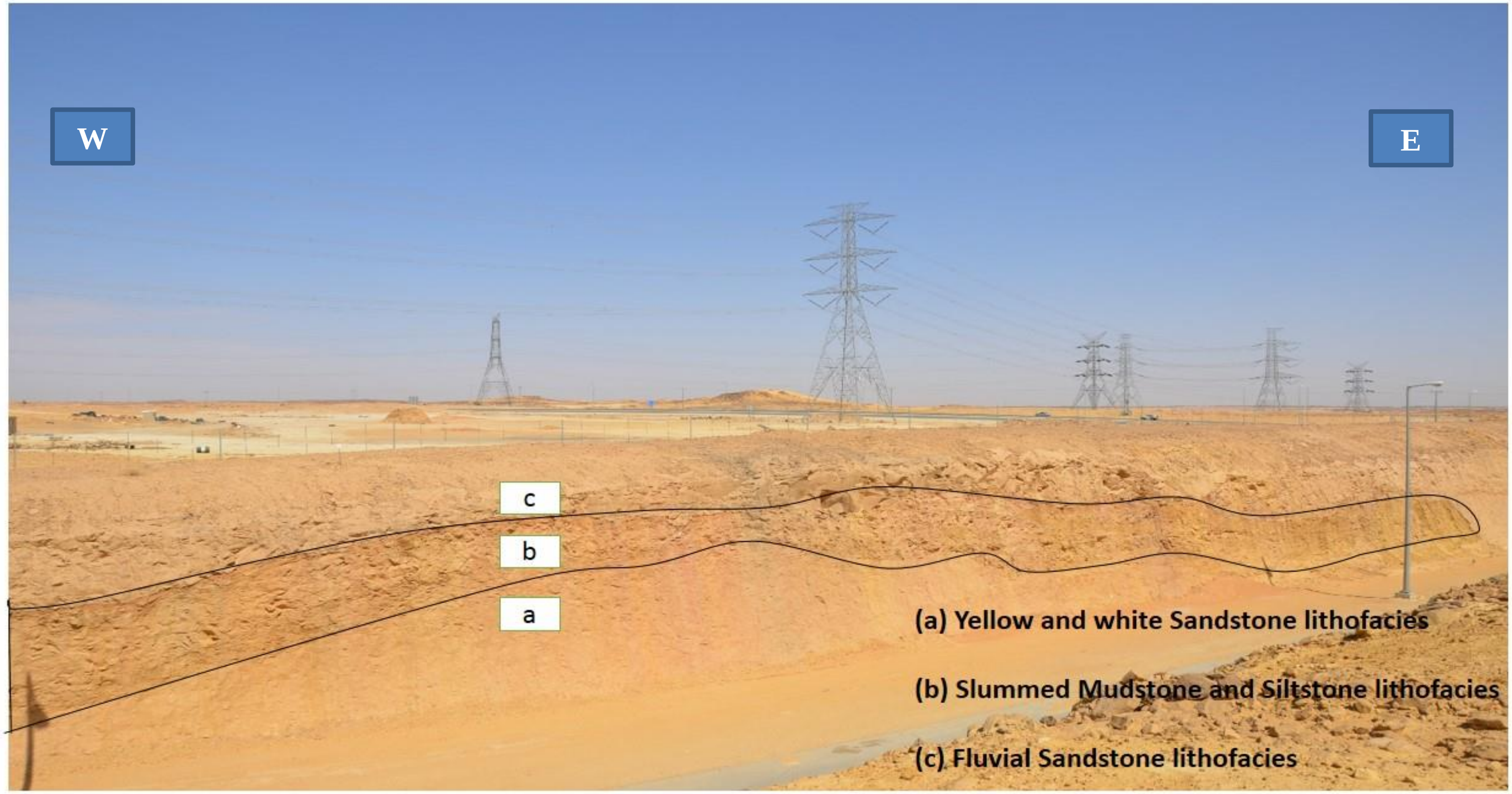

Figure 3.3 Photograph of the north side of the outcrop at Sarah paleovalley describes slumped siltstone and mudstone lithofacies .

3.3 Stratigraphic Sections

Detailed stratigraphical studies were conducted along selected vertical sections to create the vertical stratigraphic sections, which help to study and describe the vertical lithofacies changes. The main lithologic feature for the studied paleovalley on outcrop scale is the presence of large to huge boulders of diamictite transformed by glacial movement along the paleovalley. The huge boulders of diamictite indicate short distance of transformation and closer distance from the source of glaciation movement to the area of deposition, as described by (Ghienne, 2011). This was confirmed on meso scale and thin section scale by the presence of poorly sorted diamictite with angular edges indicating source rock (Figure 3-4).

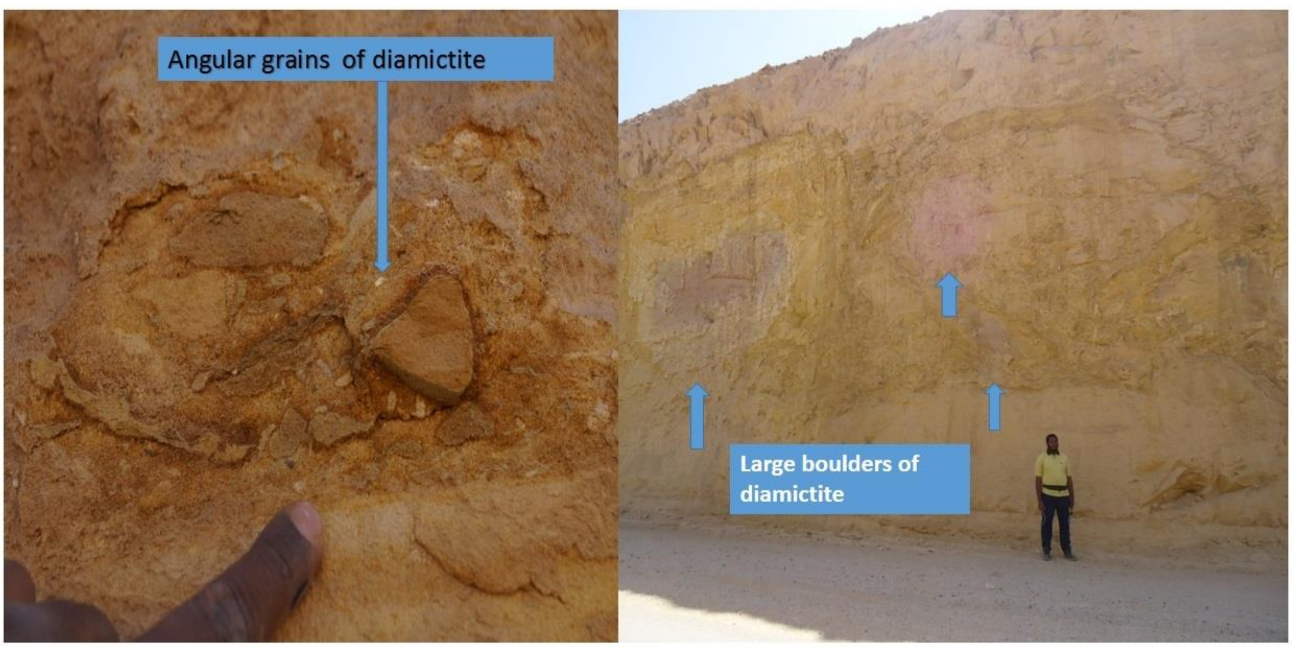

Figure 3.4 Photograph showed the stratigraphic section for location1 at Sarah paleovalley.

Section 1:

The vertical stratigraphic section for location 1 (N 26 33.708, E 43 35.758) defines clear vertical variation in lithofacies started by yellowish brown, poorly sorted, medium to coarse, diamictite texture, ferruginous sandstone lithofacies of 2.3 thickness which changed to brownish yellow, finely interbedded, slumped siltstone with thickness of about 1.7 m, to dark brown, slumped mudstone with 0.7 m thickness, and back to siltstone lithofacies with 0.5 m thickness, to yellowish brown, poorly sorted, medium to coarse, diamictite texture, ferruginous sandstone lithofacies with 2 m thickness. This lithofacies is followed by thin mudstone lihofacies about 0.3 m thick, this sequence is capped by yellow, medium to fine grain, moderately sorted, laminated fluvial sandstone with 2 m thickness. The vertical section in location 1 describes four lithofacies and with 9.5 m. (Figure 3-7).

Section 2:

The vertical lithofacies change in section 2 (N 26 33.706, E 43 35.768) started by the change from yellowish brown, poorly sorted, medium to coarse, diamictite texture, ferruginous sandstone lithofacies of 2m thickness, to 1.5 m thick white, medium to coarse grained, diamictite texture, poorly sorted sandstone lithofacies, to 1 m of brownish yellow, finely interbedded, slumped siltstone lithofacies followed by half meter of yellowish brown sandstone lithofacies, to slumped siltstone lithofacies of 1.2 m thickness, and this sequence is capped by yellow, medium to fine grain, moderately sorted, laminated fluvial sandstone lithofacies (Figure 3-8).

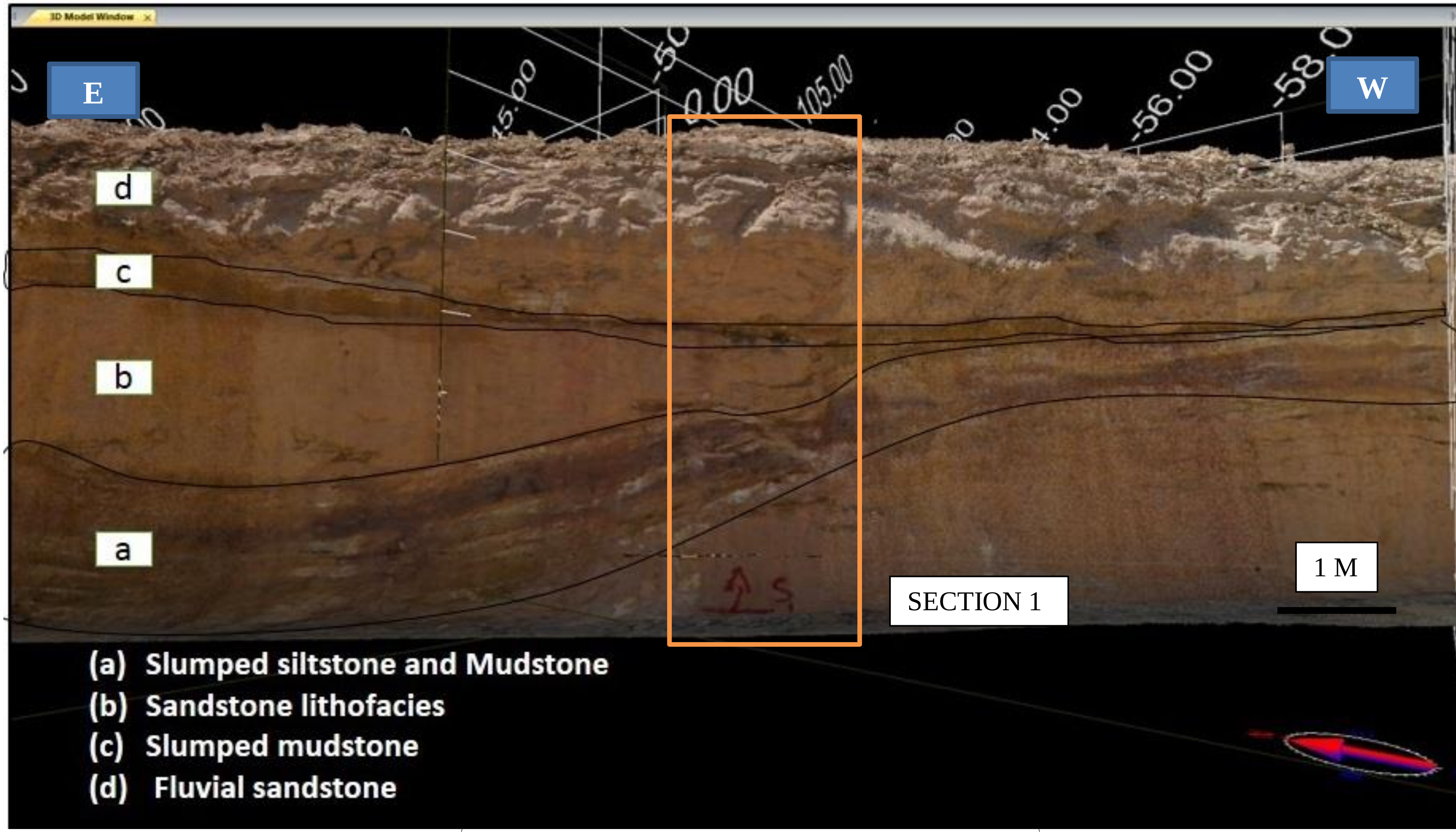

Figure 3.5 Lidar image for section 1 location at Sarah paleovalley.

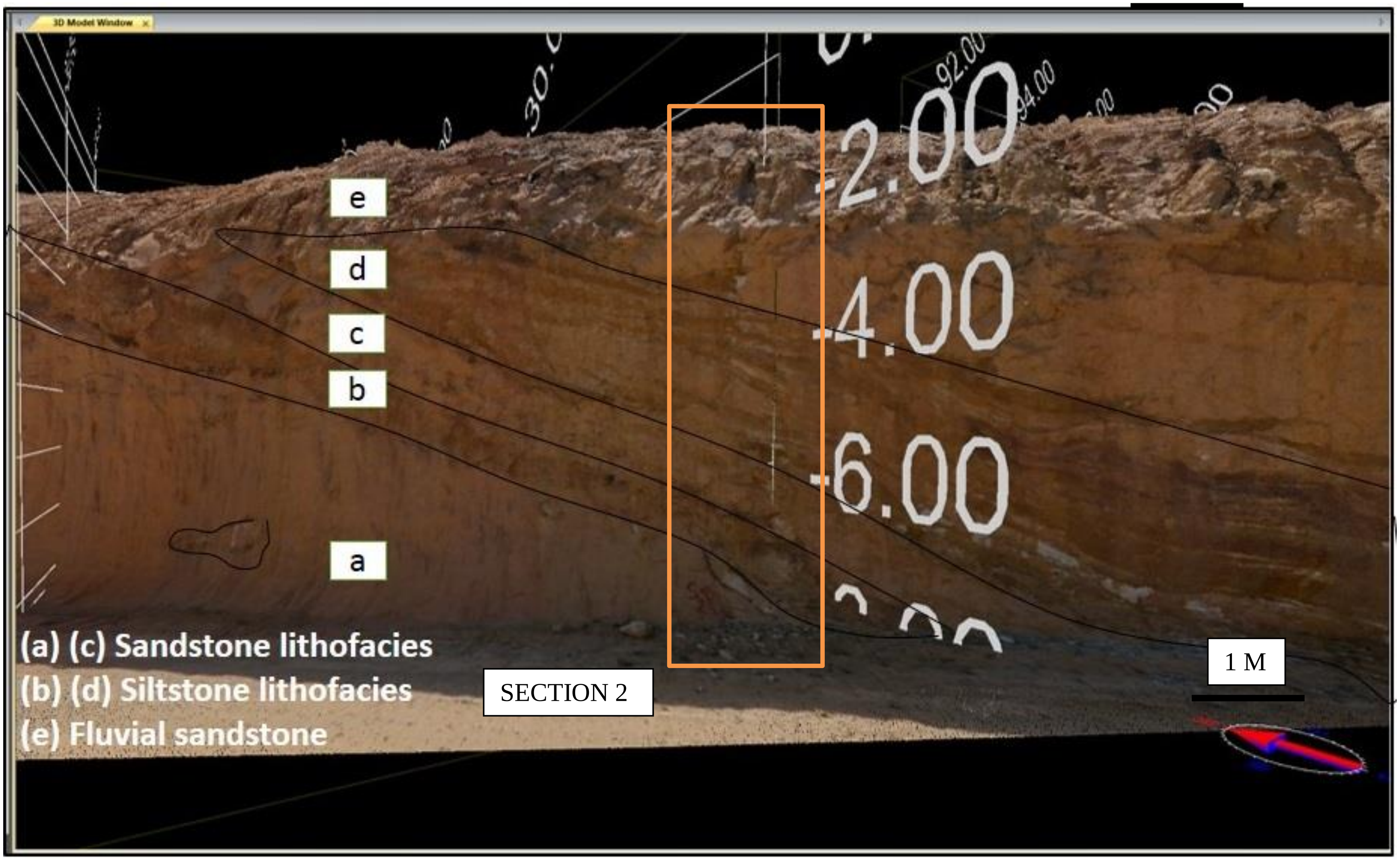

Figure 3.6 Lidar image for section 2 location at Sarah paleovalley

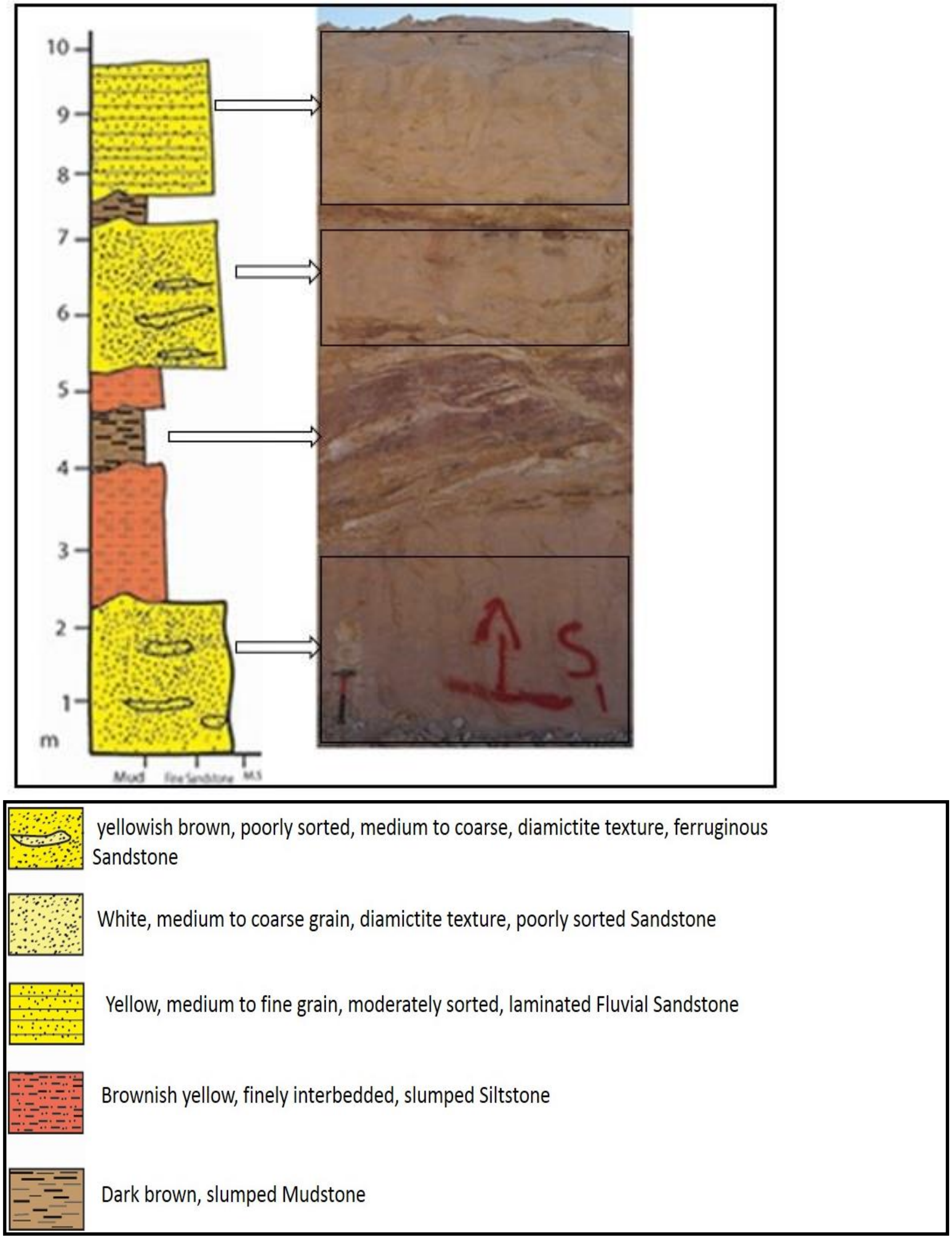

Figure 3.7 Vertical stratigraphic section for location 1 at Sarah paleovalley.

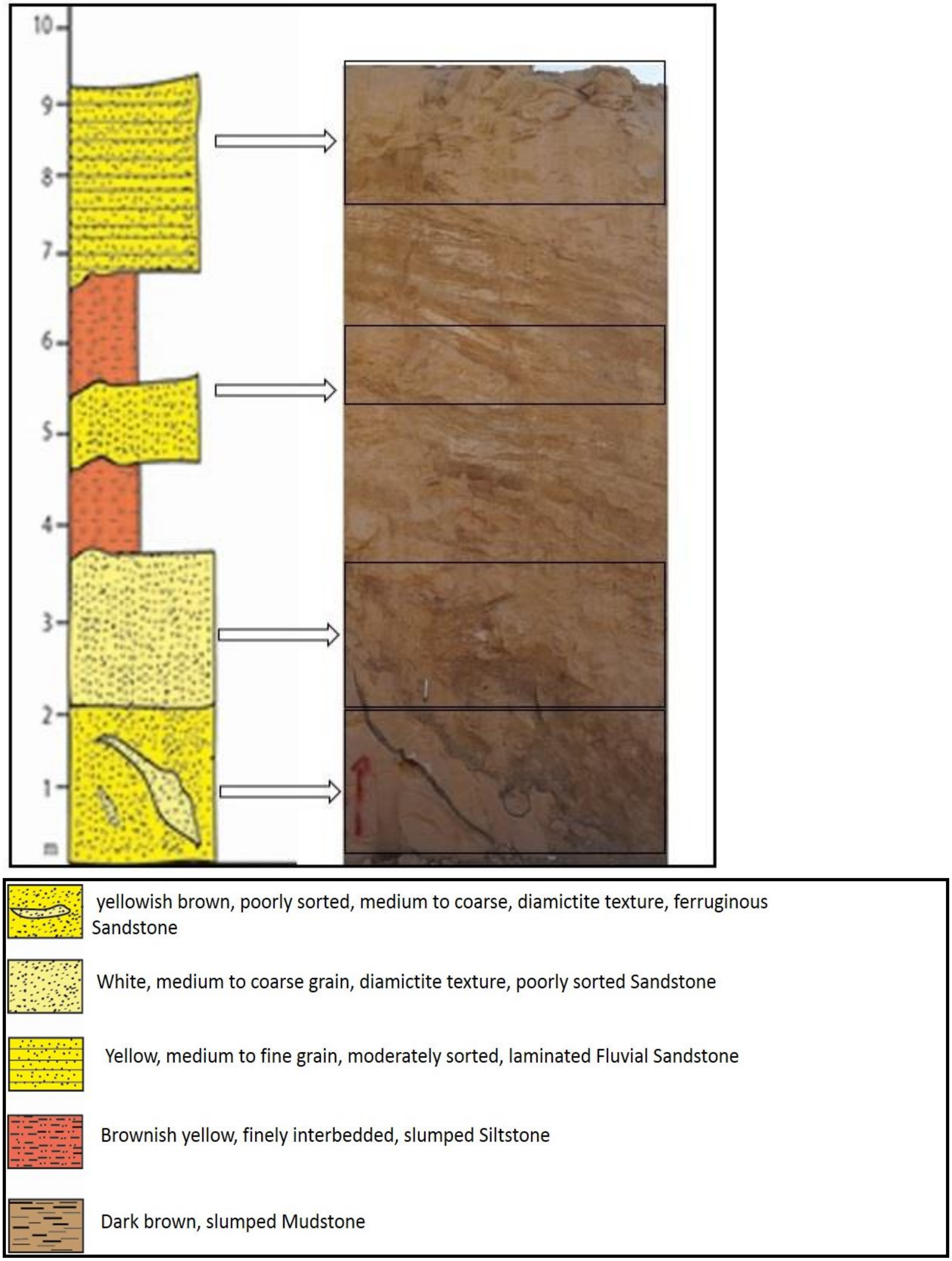

Figure 3.8 Vertical stratigraphic section for location 2 at Sarah paleovalley.

Section 3:

The (Figure 3-9) for section 3 describes three lithofacies started by yellowish brown, poorly sorted, medium to coarse, ferruginous Sandstone lithofacies with 4 m thickness that changed to 1 m of brownish yellow, finely interbedded, slumped siltstone lithofacies and the sequence is capped by 1.4 m of yellow, medium to fine grain, moderately sorted, laminated fluvial sandstone lithofacies.

Section 4:

The (Figure 3-10) for section 4 describes four lithofacies starting with yellowish brown, poorly sorted, medium to coarse, ferruginous sandstone lithofacies with 3 m thickness changing to 2.6 m of white, medium to coarse grain, diamictite texture, poorly sorted sandstone lithofacies to 0.4 m of brownish yellow, finely interbedded, slumped siltstone lithofacies to 0.7 of white sandstone lithofacies to 0.9 m of siltstone lithofacies and the sequence is capped by 2 m of yellow, medium to fine grain, moderately sorted, laminated fluvial sandstone lithofacies.

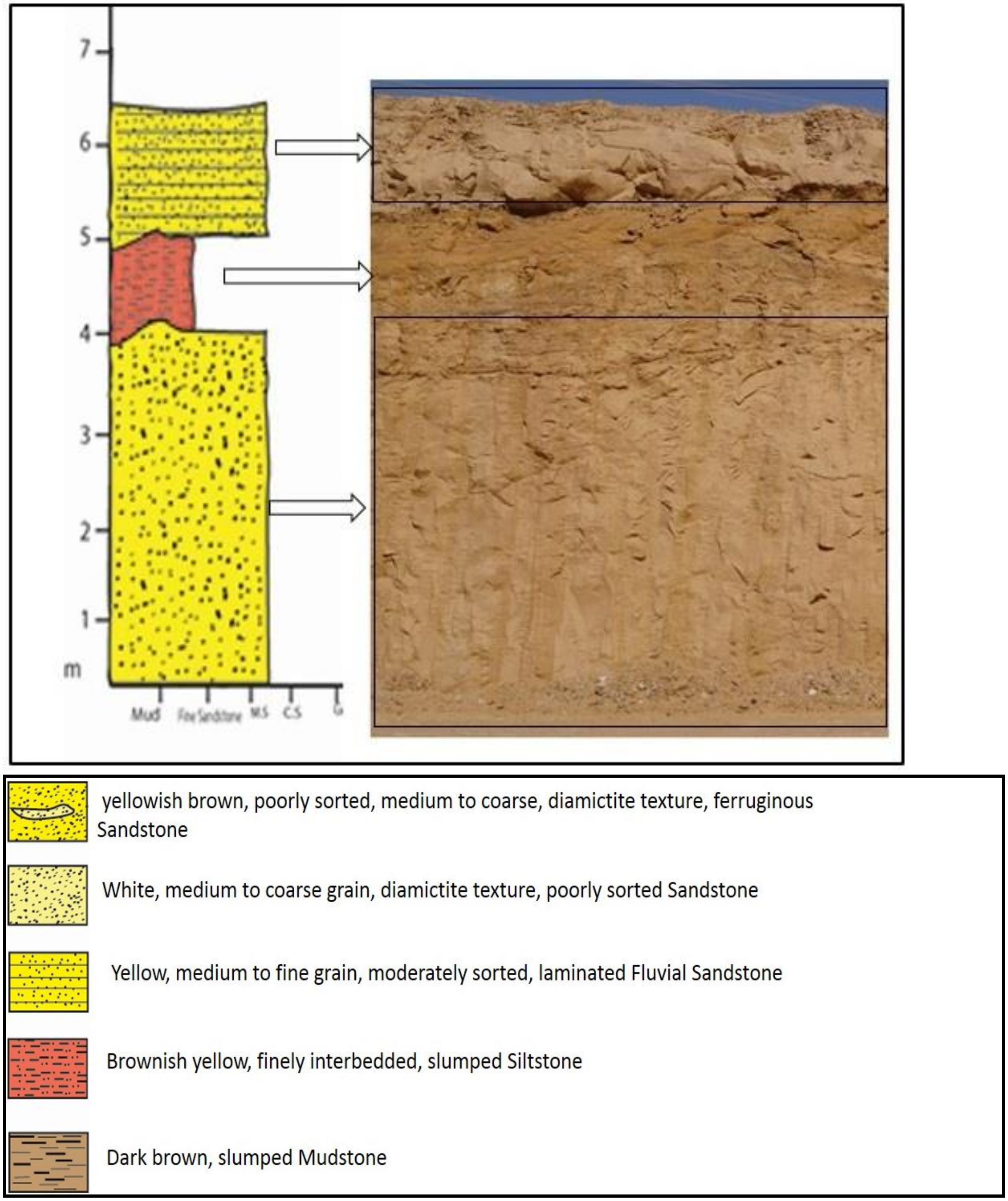

Figure 3.9 Vertical stratigraphic section for location at Sarah paleovalley 3.

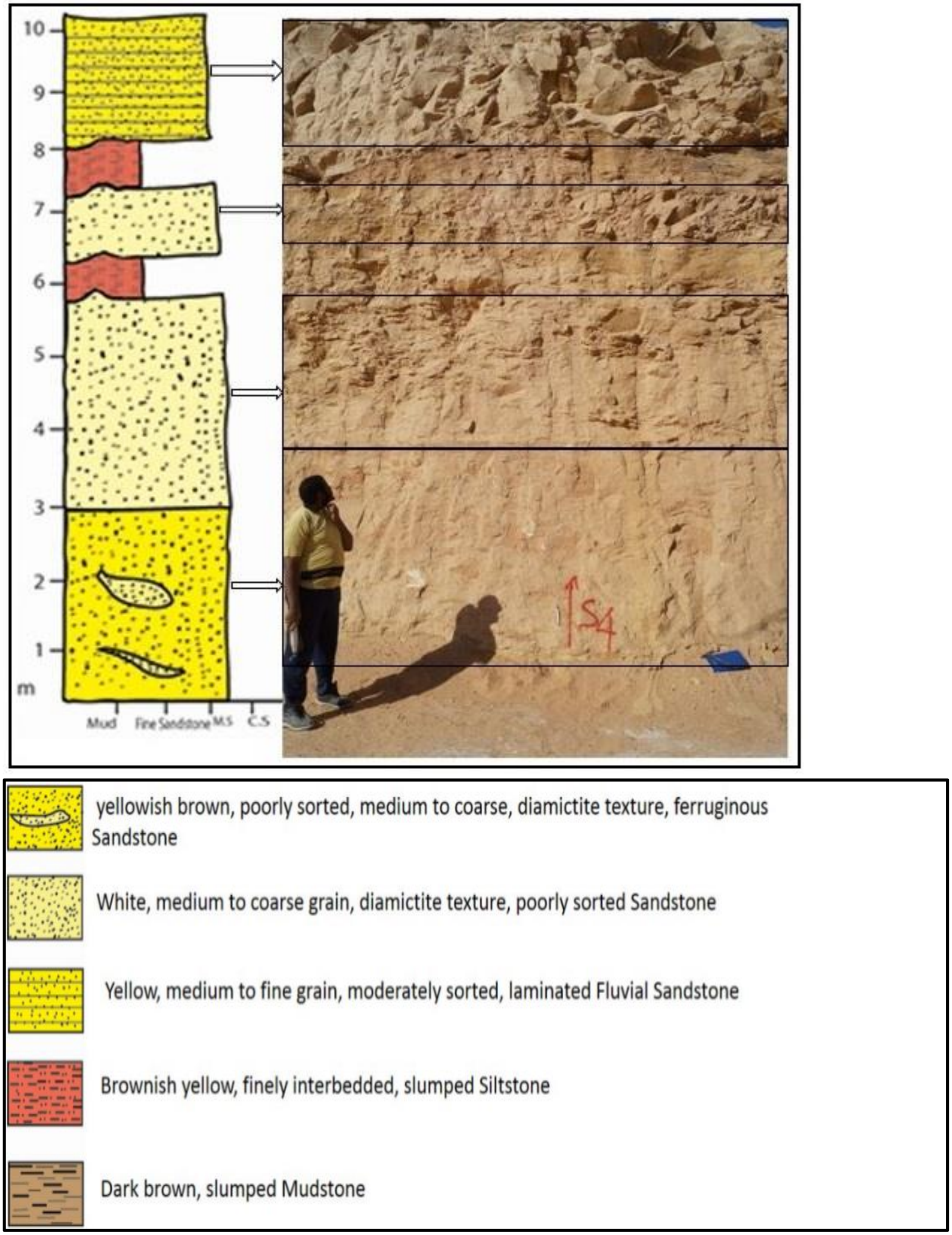

Figure 3.10 Vertical stratigraphic section for location at Sarah paleovalley 4.

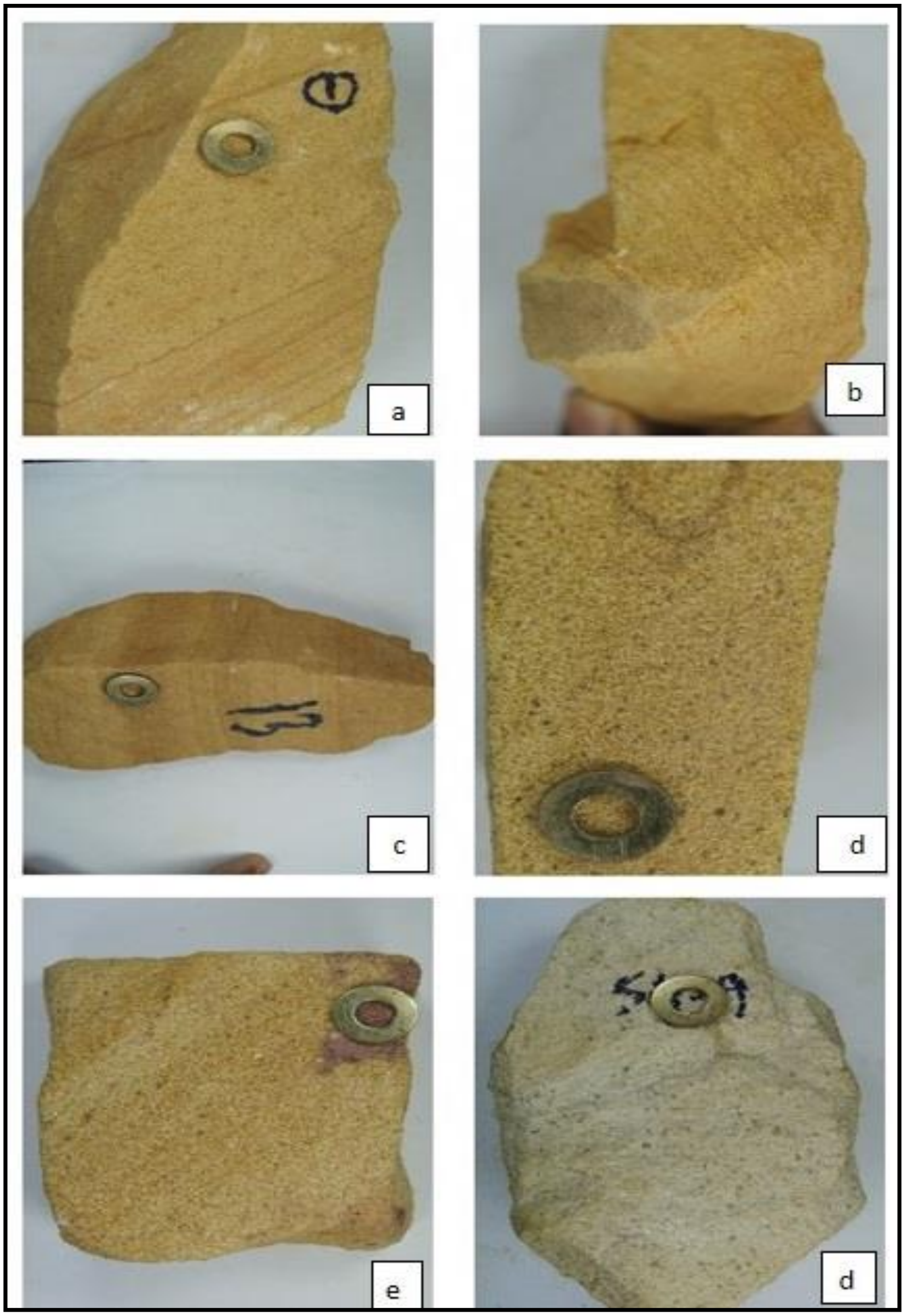

Figure 3.11 Photographs of outcrop lithofacies (a) (b) (c) photographs show the laminated sandstone (d) (e) (d) photographs show very poorly sorted sandstone with diamictite texture.

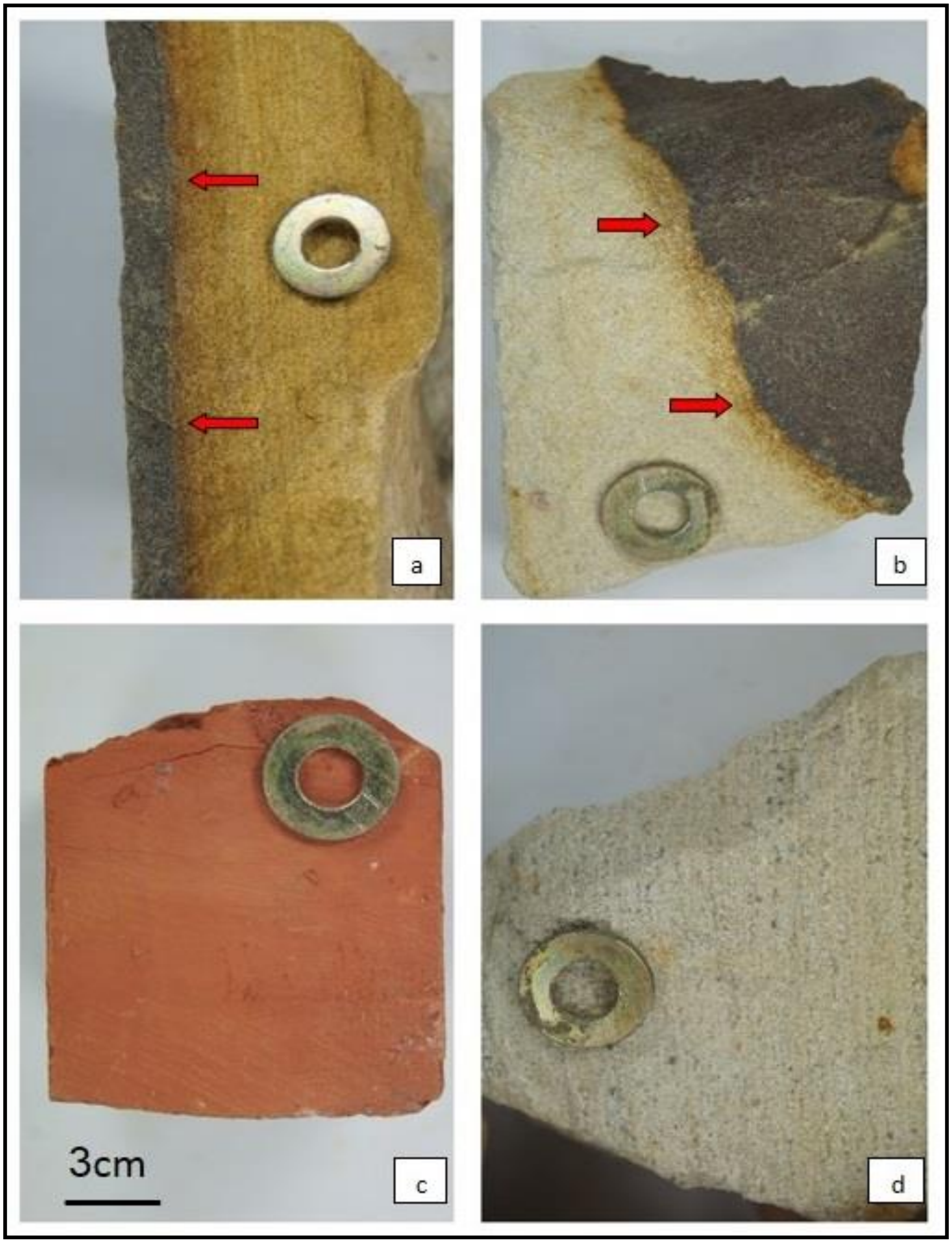

Figure 3.12 Photographs of outcrop lithofacies (a) (b) photographs show ferruginous Sandstone (c) photographs shows mudstone lithofacies (d) photographs shows very poorly sorted sandstone with diamictite texture.

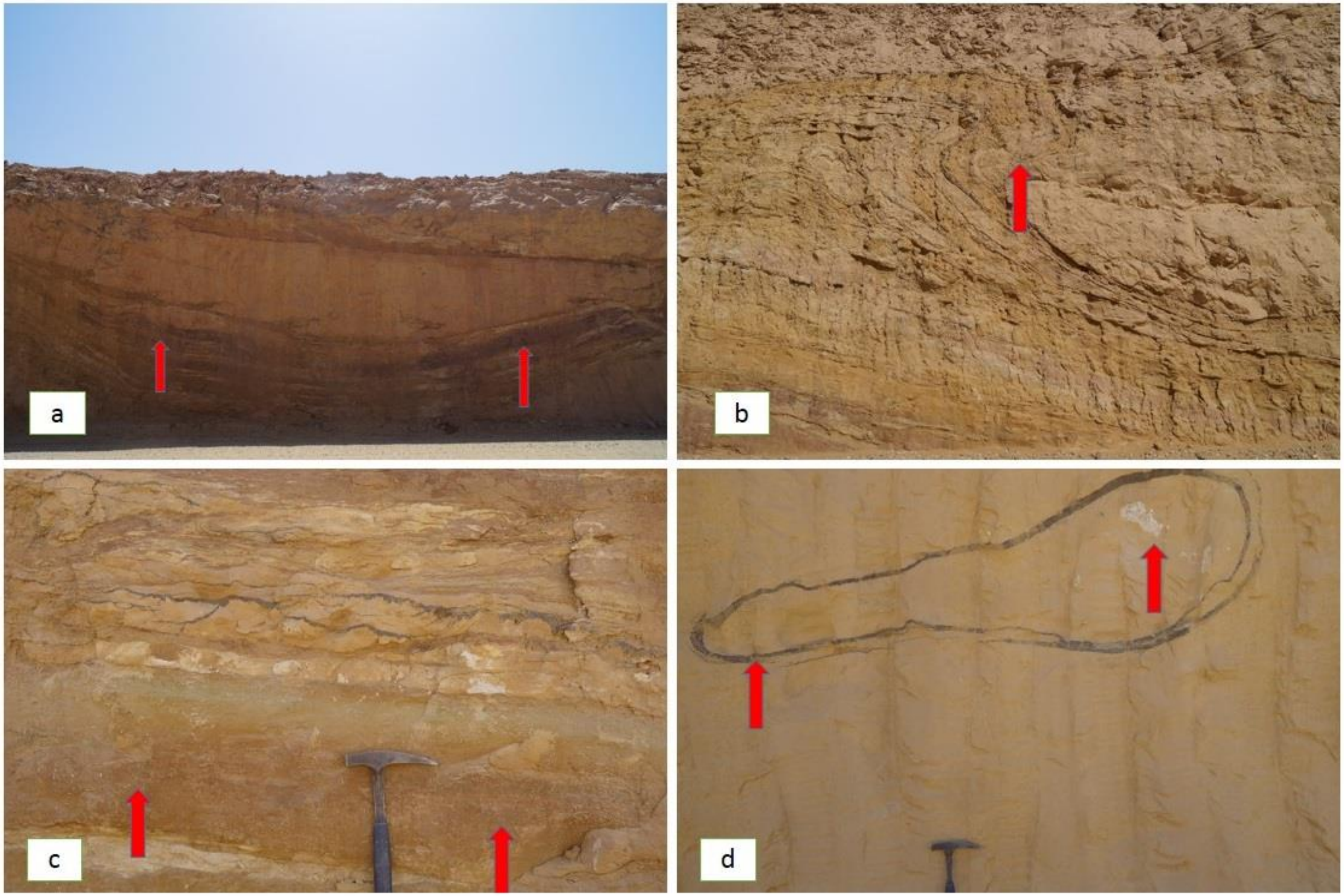

Figure 3.13 Photographs of outcrop lithofacies (a), (b) Folded and stressed siltstone lithofacies, (c) Mudstone lithofacies, (d) White Sandstone lithofacies with iron oxides

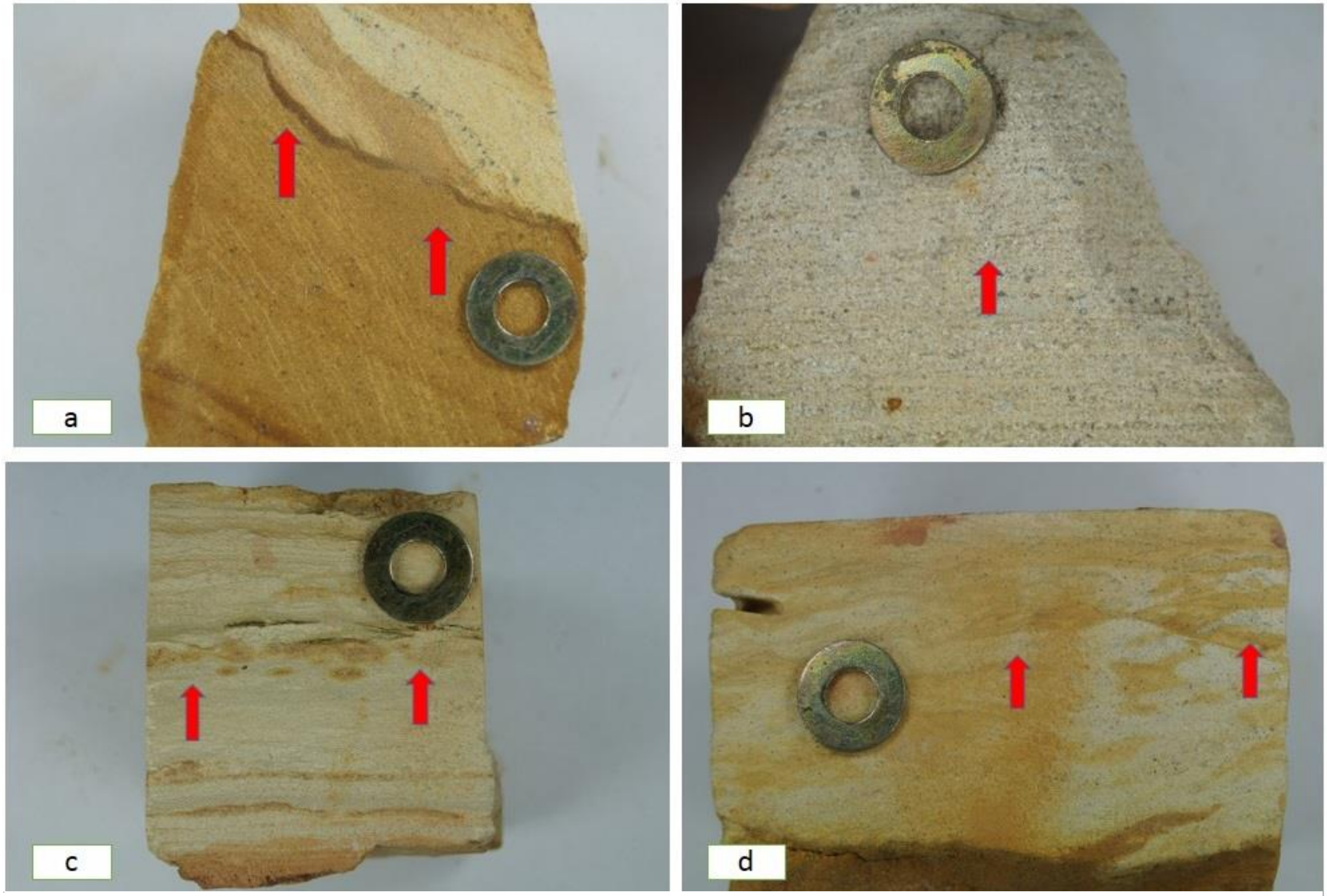

Figure 3.144 Photographs of outcrop lithofacies (a) describe the erosive boundary of siltsone lithofacies with poorly sorting , (b) poorly sorted white sandstone with clear striation nature of glaciation, (c) chaos nature of glaciation at siltstone, (d) photographs show siltstone lithofacies with scoured boundary and xeno-sandstone.

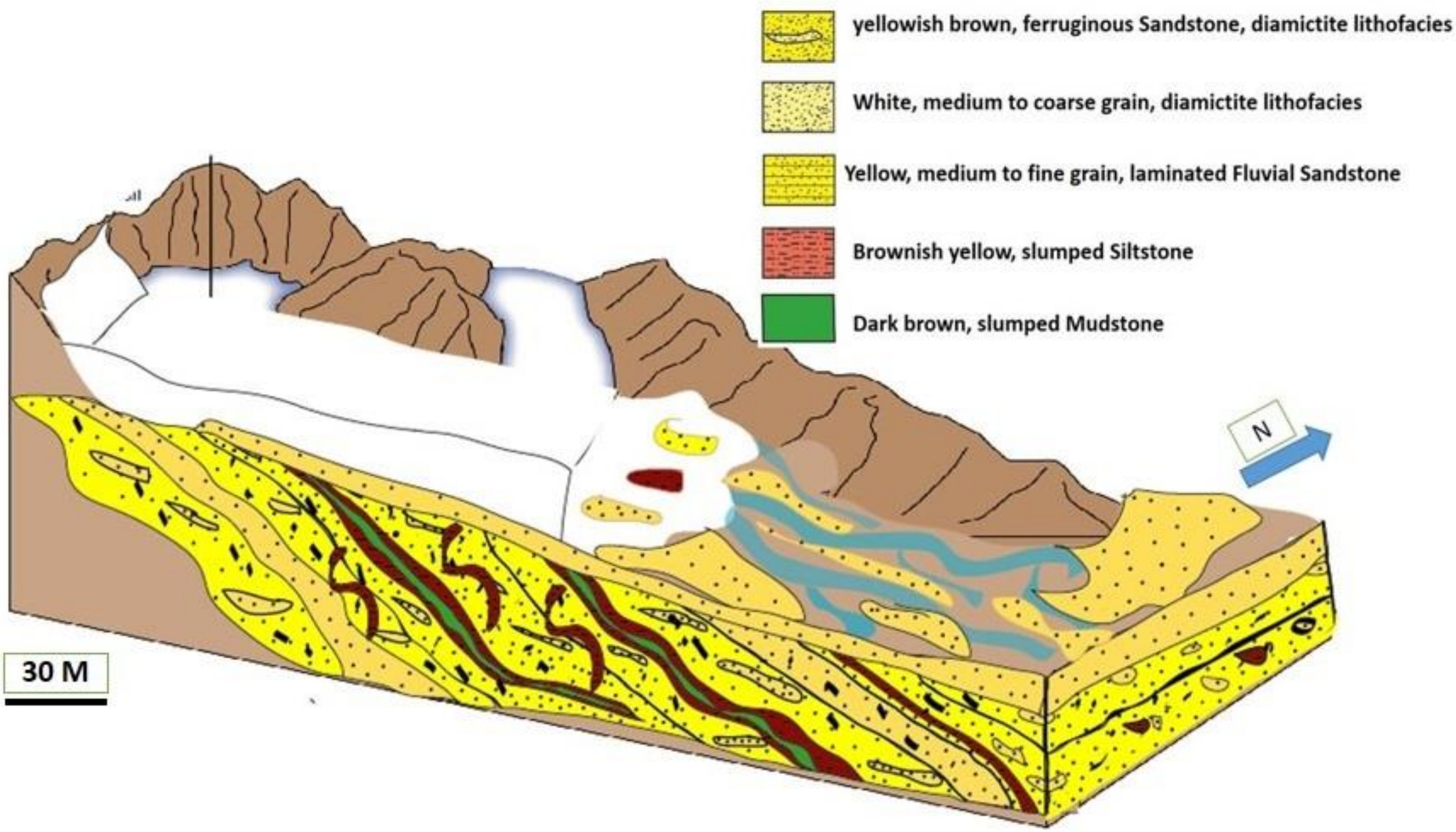

Figure 3.15 Sedimentological model describe the lithological distribution and depositional stack nature of glaciation with lithological deformation associated with glaciation such as slumping and folding at Sarah paleochannel.

3.4 Laboratory Analysis

The laboratory analysis cover petrophysical analysis (porosity and permeability), geomechanical tests, thin section Petrography, SEM and XRD.

3.4.1 Thin section Petrography

Thin section described poorly sorted angular to subangular Sandstone with iron oxides as a cementing material for most of the samples which reflect the glacial nature for Sarah paleochannel. The dominant minerals are Quartz in sandstones lithofacies and iron oxides. Some of the samples showed moderate to good visual porosity while others reflect very poor visual porosity and permeability with iron oxides as a cement materials.

The poor petrophysical properties occur manly at the boundary between different Sandstone bodies during iron transformation of iron. This boundary in the subsurface with poor petrophysical properties act as a fluid barrier for Sandstone bodies which may act positively as a seal or negatively to prevent fluid migration. Thin section petrography showed a good evidence for glacial nature for Sarah paleochannel by the presence of fractured and striated Quartz with lamination nature for mudstone and siltstone lithofacies (figure 3.15).

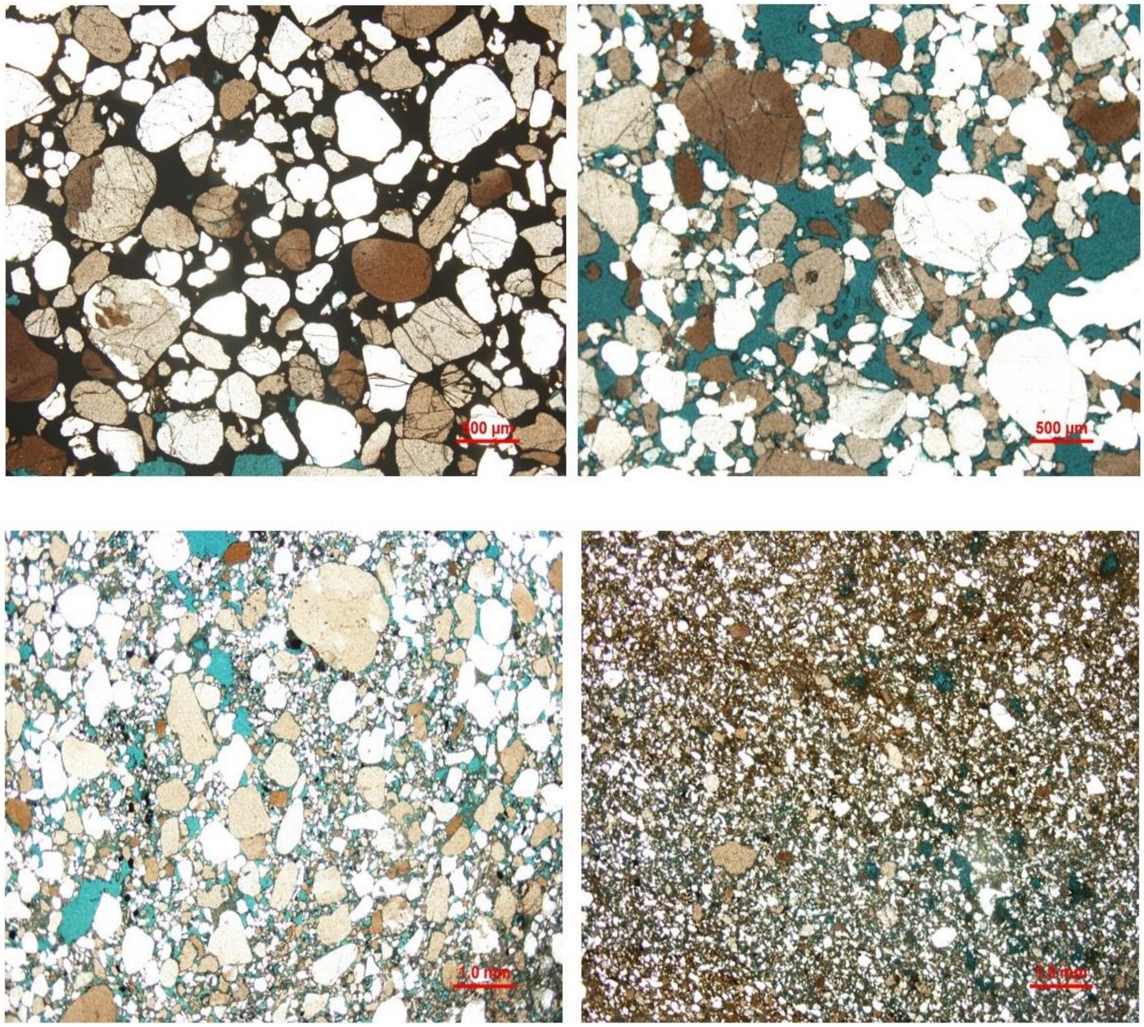

Figure 3.15 Photomicrographs for Sarah paleochannel samples (a) and (b) showed fractured and striated quartz with iron oxides as a cement materials. (c) and (d) showed poorly sorted angular sandstone with moderate to good visual porosity.

(a) Yellow sandstone lithofacies
(b) (c) White sandstone lithofacies
(d) Siltstone lithofacies

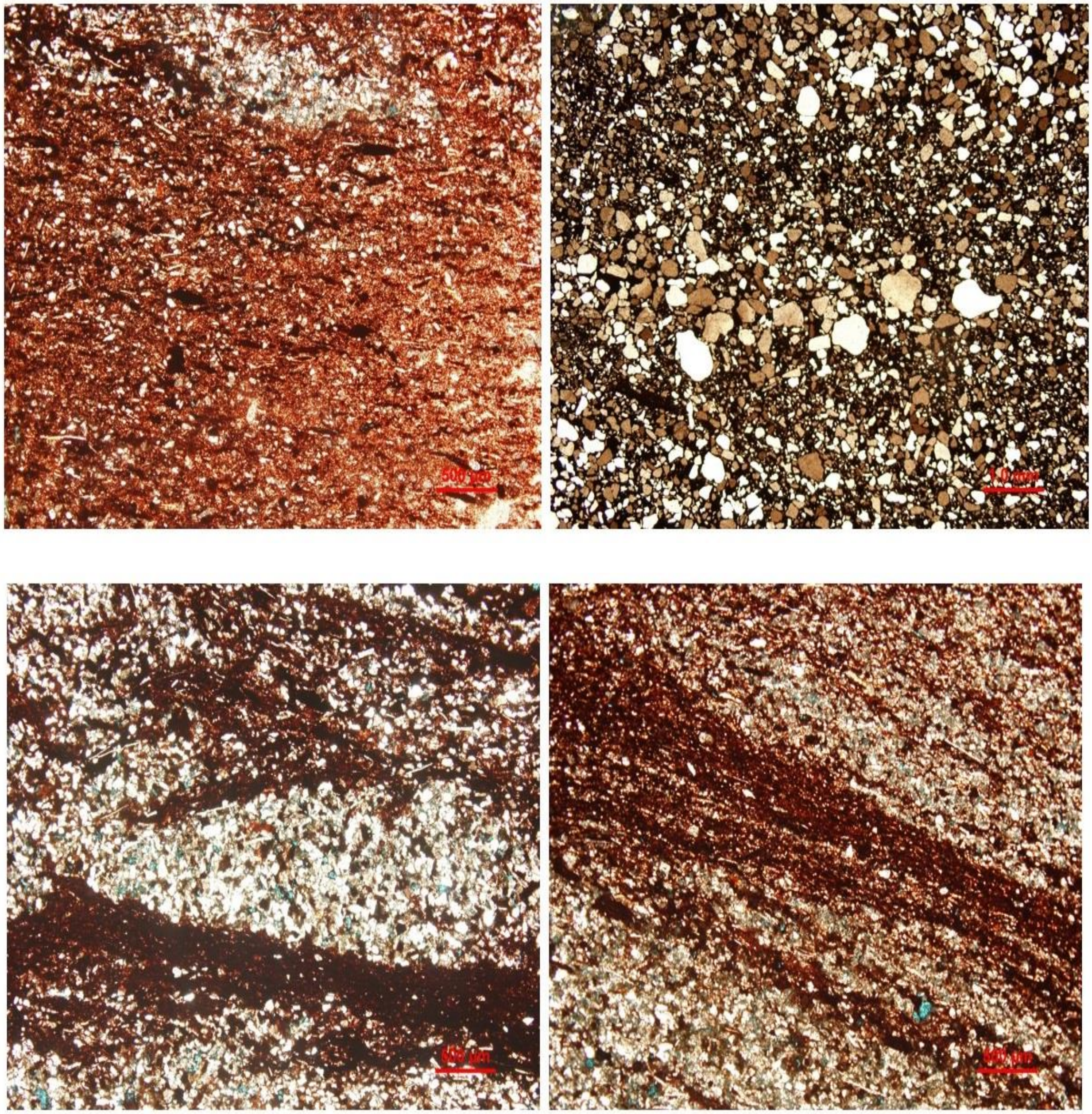

Figure 3.16 Photomicrographs for Sarah paleochannel samples (e) and (f) showed siltstone lithofaces with iron oxides as a cement material and iron concentration at the boundary between different sandstone backages (g) and (h) showed lamination nature and iron oxides concentration for siltstone lithofaces because of glacial movement and fluid transformation.

- **(a)** Ferruginous sandstone lithofacies
- **(b)** Siltstone lithofacies
- **(c)** (d) Slumped siltstone

3.4.2 SEM and XRD

Sarah Formation paleochannel samples subjected to SEM and XRD analysis to investigate the cement material and minerlogical composition for different lithofacies. The result showed quartz as the main forming mineral with Kaolinite and illite minerals. SEM result showed the relation between quartz, illite and kaolinite. Some of samples showed quart overgrowth while others showed illite and kaolinite as a cement materials in siltstone lithofacies.

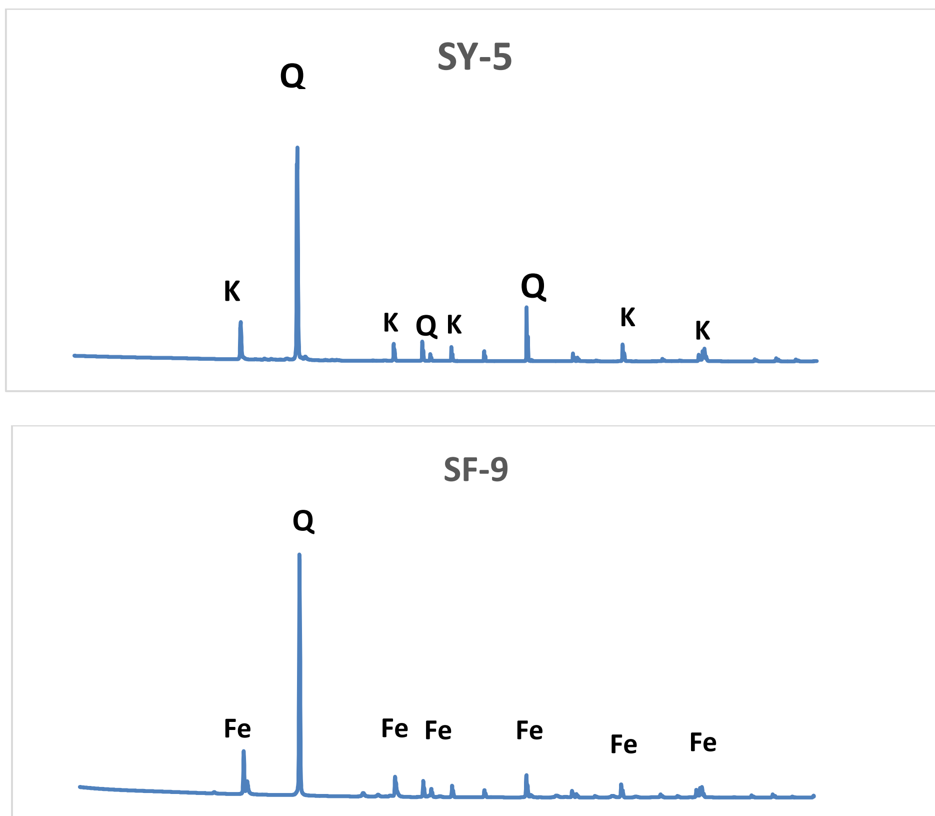

Figure 3.17 XRD results for Sarah paleochannel samples showed the dominant of quartz and the presence of kaolinite and ion oxides. Q= Quartz, K= Kaolinite Fe= Iron oxide

SY= Yellow sandstone lithofacies

SF= ferruginous sandstone

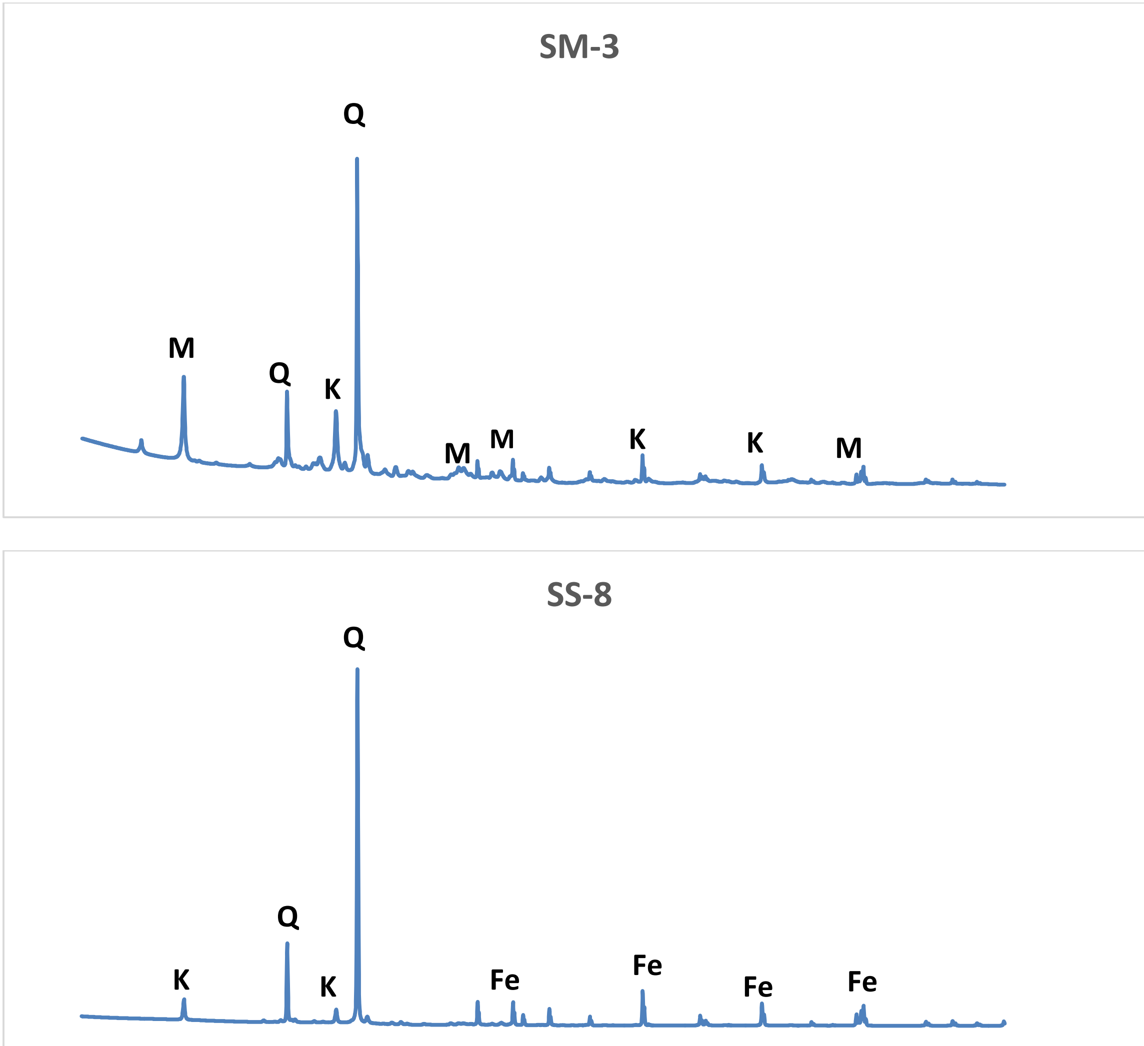

Figure 3.18 XRD results for Sarah paleochannel samples showed the dominant of quartz with the presence of iron oxides, Kaolinite and muscovite. Q= Quartz, K= Kaolinite Fe= Iron oxide, M= Muscovite.

SM= Slumped mudstone lithofacies

SS= Fluvial sandstone lithofacies

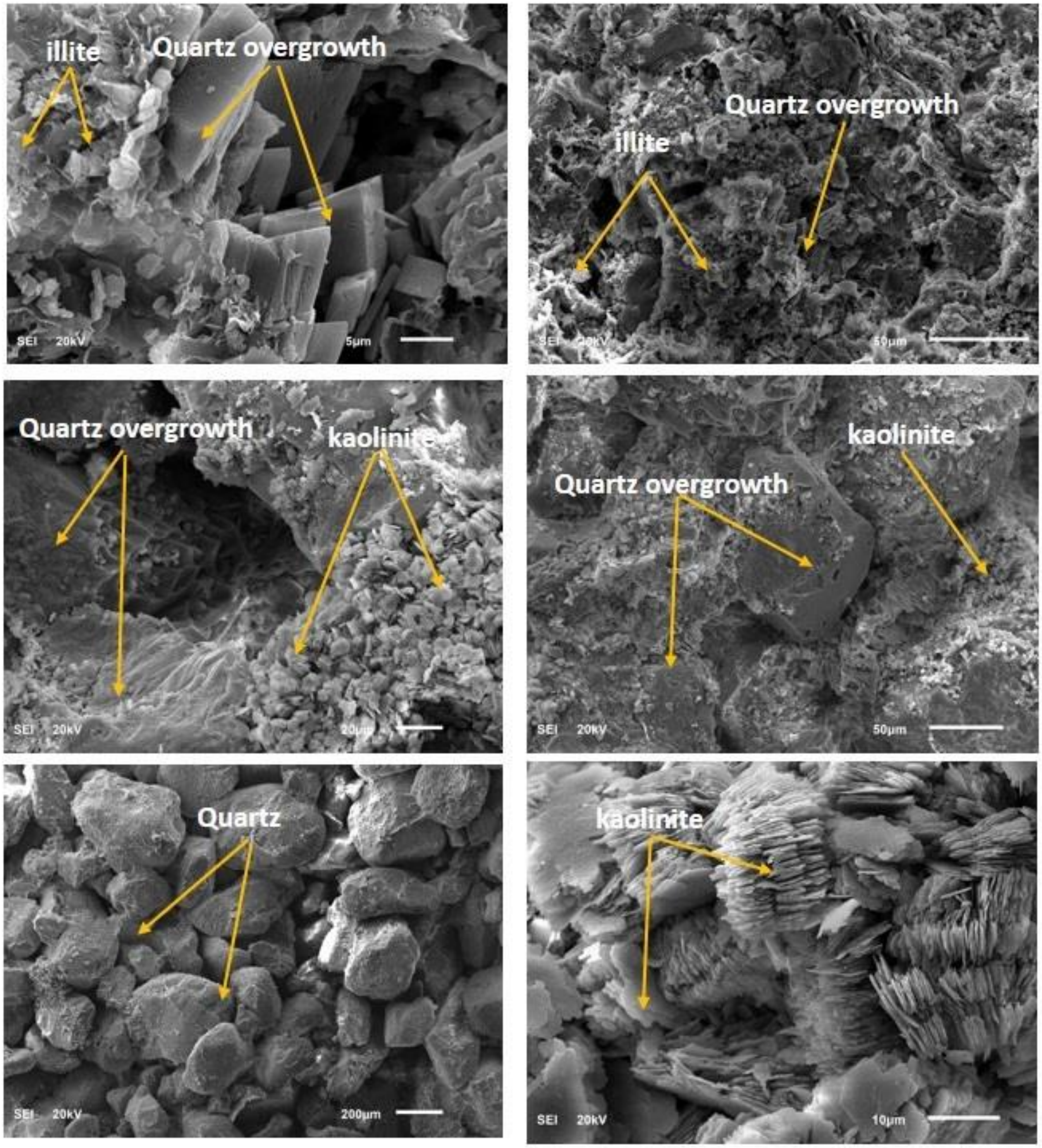

Figure 3.19 SEM Photomicrograph of glacial Sarah Formation sandstone (a) (b) showed quartz overgrowth with illite in siltstone lithofaces (c) (d) showed kaolinite and quartz overgrowth (e) showed moderately sorted sandstone (f) showed the platey structure of kaolinite.

(a) (b) Mudstone lithofcaies   (c) (d) Siltstone lithofacies
(e) White Sandstone lithofacies   (f) Mudstone lithofacie

3.4 Summary and discussion:

The field work conducted to investigate the lithological and stratigraphical heterogeneity for Sarah paleochannel. Four sections selected based on vertical and horizontal heterogeneity and also to include all of the lithofacies in the paleochannel. The stratigraphic section revealed on main five lithofacies which are, yellowish brown, poorly sorted, medium to coarse, diamictite texture, ferruginous sandstone lithofacies, brownish yellow, finely interbedded, slumped siltstone lithofacies, slumped mudstone lihofacies, white, medium to coarse grained, diamictite texture, poorly sorted sandstone lithofacies and yellow, medium to fine grain, moderately sorted, laminated fluvial sandstone lithofacies. This lithofacies studied in micro scale using thin section, SEM and XRD. Thin section result showed the fractured quartz and striation with very poorly sorted lithofacies which known to characterized the glacial environment. SEM result showed the growth of quartz and the presence of mudstone minerals such as illite and kaolinite and confirmed by XRD measurements which showed dominant of sandstone and mudstone minerals. Lithostratigraphical model created based on the result helped to understand the lithological heterogeneity and lithofacies distribution in Sarah paleochannel.

CHAPTER 4

Fracture Characterization

Types and Nature of Fractures Association at Sarah Paleochannel

4.1 Introduction

Fractures are described the planes that lost its cohesion along the rock units. The physical characterization of fractures in rock units are 1) the fracture surface is planer 2) the fracture surfaces are parallel 3) the ratio between displacement and fracture length is small (Pollard and Aydin, 1988). The fracture characteristics in a rock mass may be controlled by different geological parameters such as porosity, structural setting, composition and grain size (Nelson, 2001). One of the main objective of this study is investigate the relationship between lithologic characteristics and fracture characterization. Laubach et al., (2009) define the fracture unit as a lithologic unit that has homogeneous fracture distribution. The fracture unit is characterized by the fracture attributes that have direct relation with the geomechanical unit. Therefore, each geomechanical unit hase specific fracture characteristics related to the bed thickness, tectonic setting and lithologic content. The influence of lithology on fracture distribution defined by Odling et al. (1999) as stratabound and non-stratabound fracture systems. Stratabound fracture system (Figure 3-1(a)) developed when fracture distribution confined to the lithologic layering, while non-stratabound fracture systems (Figure 3-1(b)) developed where the fracture are not confined to the rock unit layering.

The deformation modes near the fracture proposed by (Kanninen and Popelar, 1985). Mode I fracture when the rock units moves away from each other and perpendicular to the fracture plane (figure 3-2a). Mode II take place when the rock units past each other and moves parallel to the fracture planes (figure 3-2b). Mode III occurs when the rock units moves with angle to each other and cased by the shear displacement (Figure 3.2c). Each type of fracture modes have specific characteristics to the reservoir quality. Mode I fracture type represents the best type for reservoir quality which results open fracture type while Mode II Mode III results closed to resistive fracture.

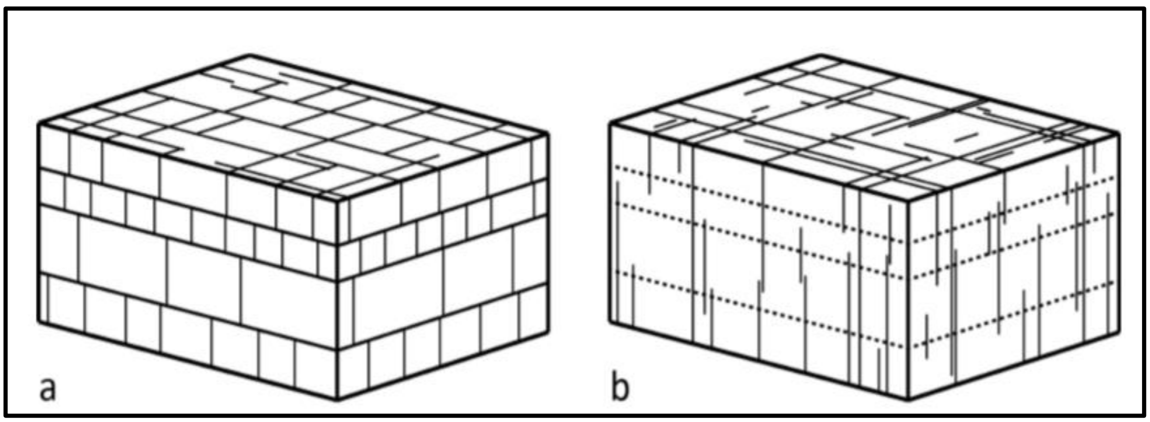

Figure 0.2 The major features of the (a) stratabound and (b) non-stratabound theoretical end members, figure from Odling et al. (1999).

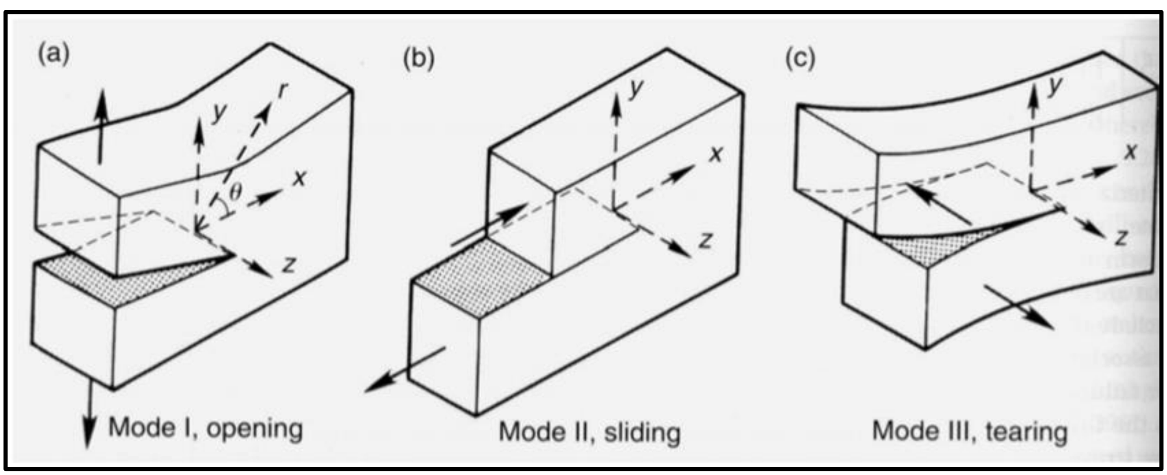

Figure 0.1 Fracture mode types a) Mode I (opening mode) b) Mode I (sliding mode) c) mode III (tearing mode)

Gui et al., 2013 studied the reservoir simulation and geomechanical analysis to optimize hydraulic fracture for Tarim basin tight reservoir in China, they came up with flow chart to establish successful fracture simulation model (Figure 3-3) which is mainly depending on subsurface well data (geology, well test, drilling, wireline data. Core and FMI images help to understand the natural fracture characterization and the geomechanical model. The fracture optimization model mainly depends on the study of natural fracture and the geomechanical characteristics. The problem of this study is the data limitation, since most of fracture in the tight reservoir are subseismic scale fracture. The advantages of the study of the fracture characteristics at Sarah paleochannel outcrop are, the accuracy in fracture measurements, overcome the data limitation and to study the fracture at reservoir scale and even in regional scale.

Sarah formation is consider as tight sandstone reservoir in the subsurface. Successful exploration in tight reservoir depend mainly on the establishment of successful fracture model, which is the major factor for successful injection process.

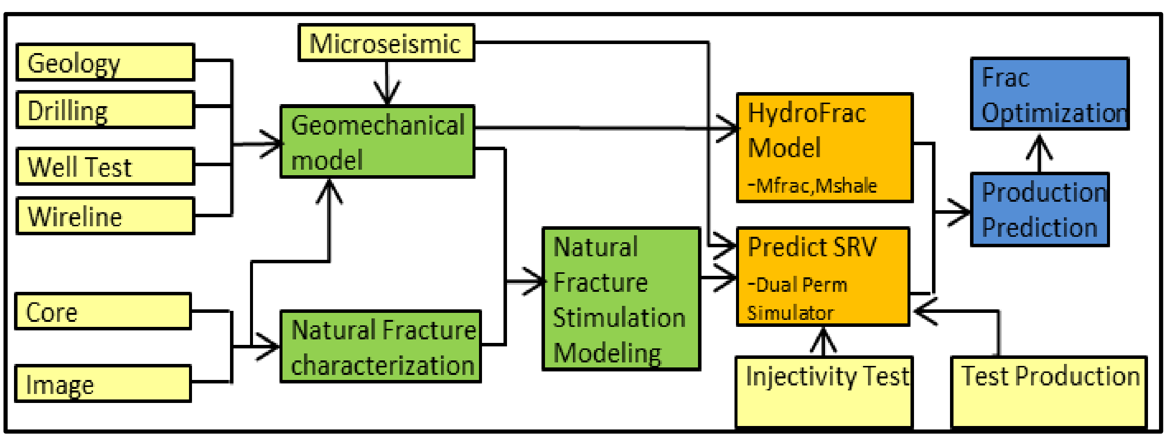

Figure 0.3 Flow chart to establish successful fracture simulation model. (Gui et al., 2013)

4.2 Fracture Characterization

The fractures in the study area are characterized using scan line method and field measurements. The fractures in the studied outcrop are mostly oriented NW, SE or EW directions. The fracture characterization for Sarah Formation is not been studied on outcrop scale, except subsurface work done by Bukhamseen et al. (2010) who established a successful fracture simulation model for Sarah tight gas reservoir in Rub Al-Khali Empty Quarter of Saudi Arabia.

The fractures in the study area describe one set of the fractures sheared and followed the direction of the glacial flow to form unconformity surfaces separating different sandstone packages. The fractures are a major factor in geomechanical unit characteristics, which affect the response of the lithologic units to the applied stress. In the outcrop, the fractures are located and distributed in the brittle lithofacies, while the ductile lithofacies does folding in response to the stress applied. The fractures in the brittle lithofacies are subjected to diagenetic processes. The diagenetic process fills the fractures with gypsum and iron-bearing cement. Therefore, this type of fracture decreases the reservoir quality and acts as a fluid barrier.

Melvin and Norton (2013) proposed a model for the glaciation mechanism in Unayzah formation (Figure 3-4)**.** The model defines thrusting boundaries and shear zones resulting from the glacial movement. The shear zones and thrusting boundaries found in the studied area are associated with horizontal to sub horizontal features along the direction of the glacial flow. The sheared and thrusting boundaries represent the unconformity boundary separating different glacial periods. The thrusting boundaries are characterized by the presence of ionization and ferruginous sandstone with no to very low porosity, which acts as a fluid barrier preventing the fluid to move between different strata. The studied outcrop have the same characteristics of Melvin and Norton (2013) model as shown on the figure below.

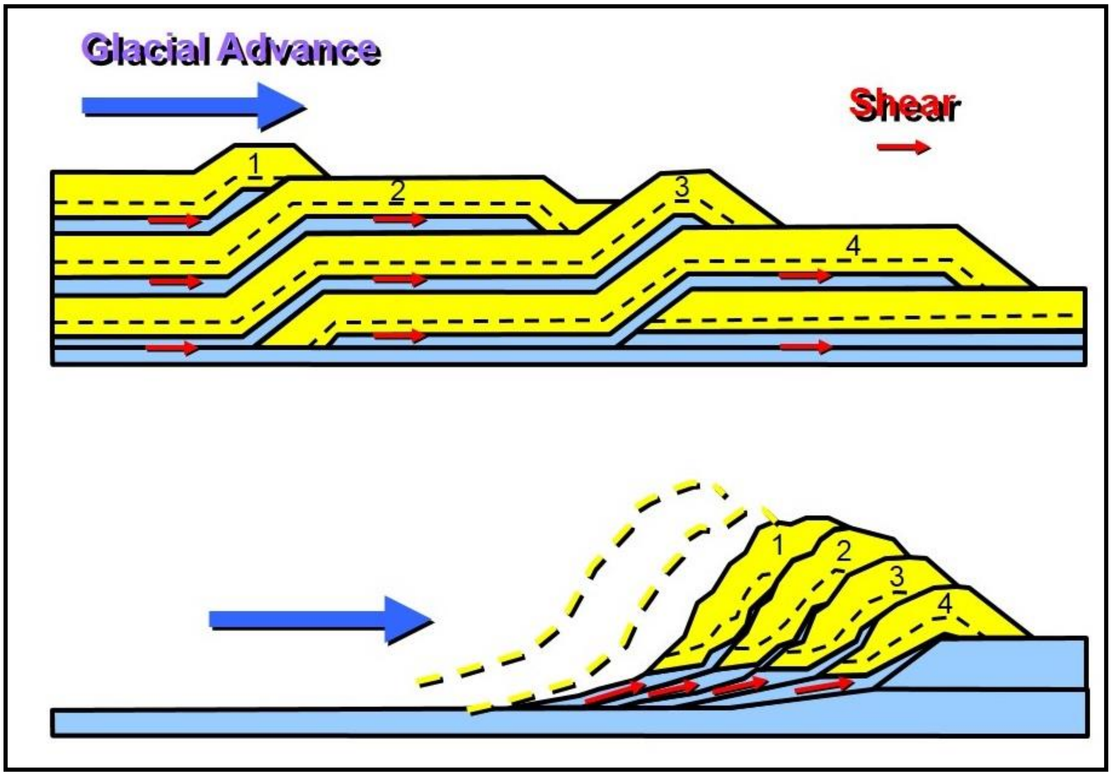

Figure 0.4 Glacio-tectonic stack model for glacial push moraines (Melvin, J., and Norton, A., 2013)

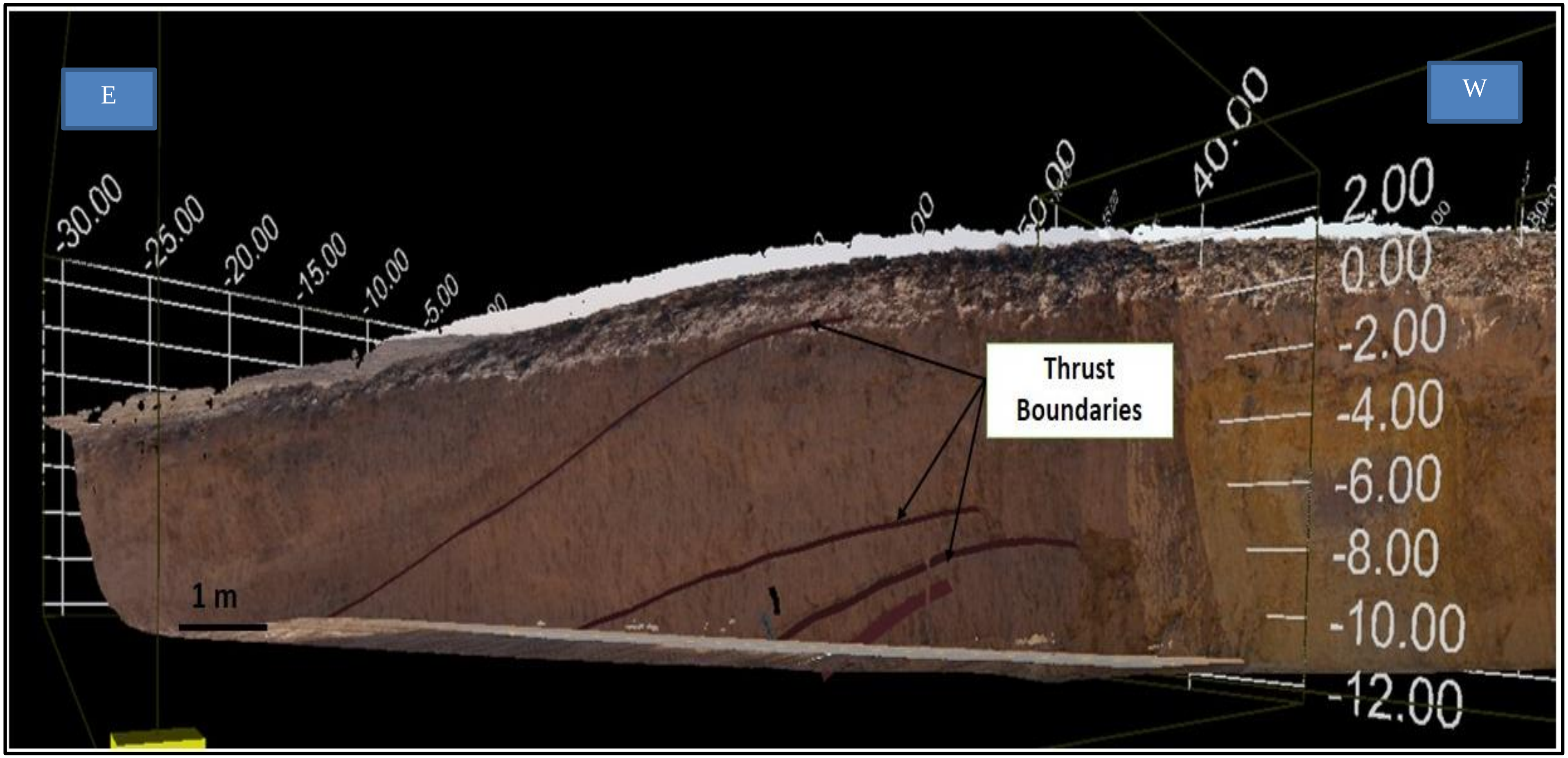

Figure 0.5 Lidar image describes Stacking Mechanism of Sarah paleovalley, the thrust boundaries represent lithological boundary separate between two different glacial events

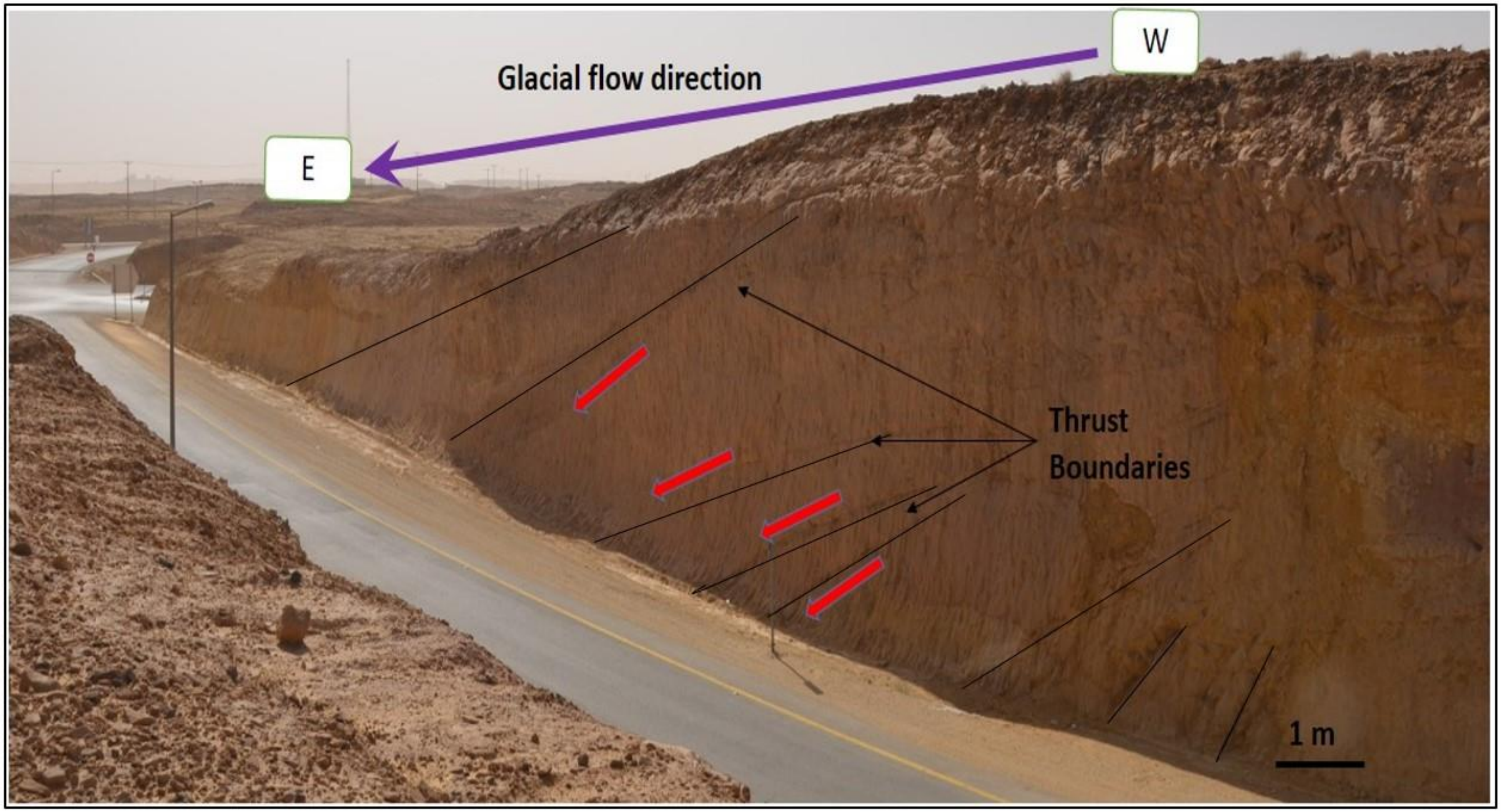

Figure 0.6 Sarah Paleovalley stack pattern, thrust boundaries and glacial flow direction the thrust boundaries represent lithological boundary separate between two different glacial events

The (Figure 4-7) below describes the relation between thrust fractures, which represent unconformity surface, and the vertical fracture which cuts across thrust fractures. The thrust fracture is syn-depositional, which resulted from glacial movement and took the dip of the older strata. The vertical fractures are considered younger in age because they cut~~s~~ across the syn-depositional fractures and its open fractures are characterized by 4 to 6 fractures in 2 meters. The fractures change their direction where the lithology changes from sandstone to siltstone or mudstone. The fracture intensity calculated by using scan line method, which describes 6 fracture per 2 meter distance.

4.3 Types of Fractures Modes

The three types of fracture modes are identified at the study area

4.3.1 Mode I and Mode II fracture types

Mode I, which is opening mode fracture and Mode II, which is sliding mode. The open fracture cut the thrust fractures and considered younger in age than the thrust fractures. The opening fractures increase the reservoir quality while thrusting fracture act as a barrier for fluid movement and decrease the reservoir quality. The two types of fracture modes are detected (Figure 4-7) at Sarah Paleochannel with three set of fractures oriented E-W and NW-SE directions. The E-W fracture sets showed preferred propagation to the lithologic composition, which can as unit have different fracture properties confined with the lithologic change of rock units (Figure 4-9).

4.3.2 Mode III fracture type

The shearing fracture mode (Mode III) also found at the eastern wall of the paleovally describe shearing mechanism of fracturing. The sheared fractures are also syn-depositonal fracture ranging between closed to resistive fractures and have E-W strike direction. The shearing fractures are common in glacial environment because of glacial deposition mechanism. The scale of shearing fractures are sub-seismic scale and it is very difficult to detect the sheared fractures at the subsurface. This mode of fracture types resulted closed fractures filled with filling materials such as ferrugination and gypsum. (Figure 4-13) shows a shear fracture which acts as a fluid barrier for fluid movement

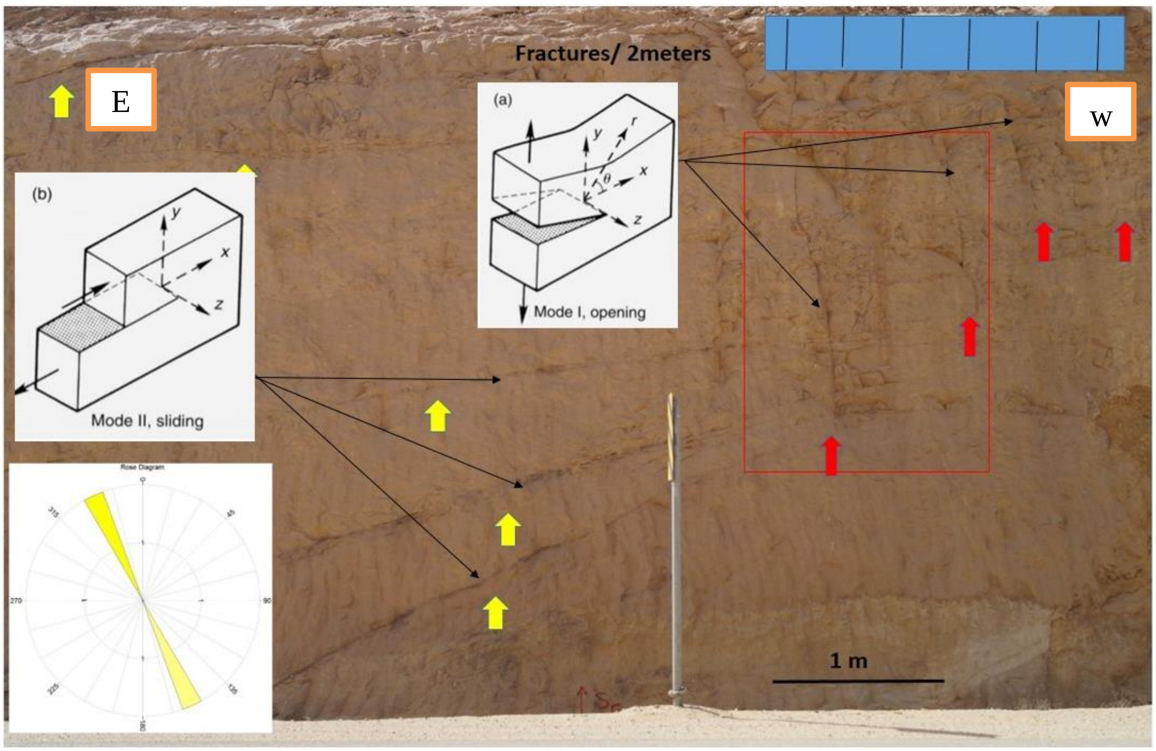

Figure 0.7 Thrust fractres and open fractres relationships with fracture intensity and modes Sarah Paleochannel

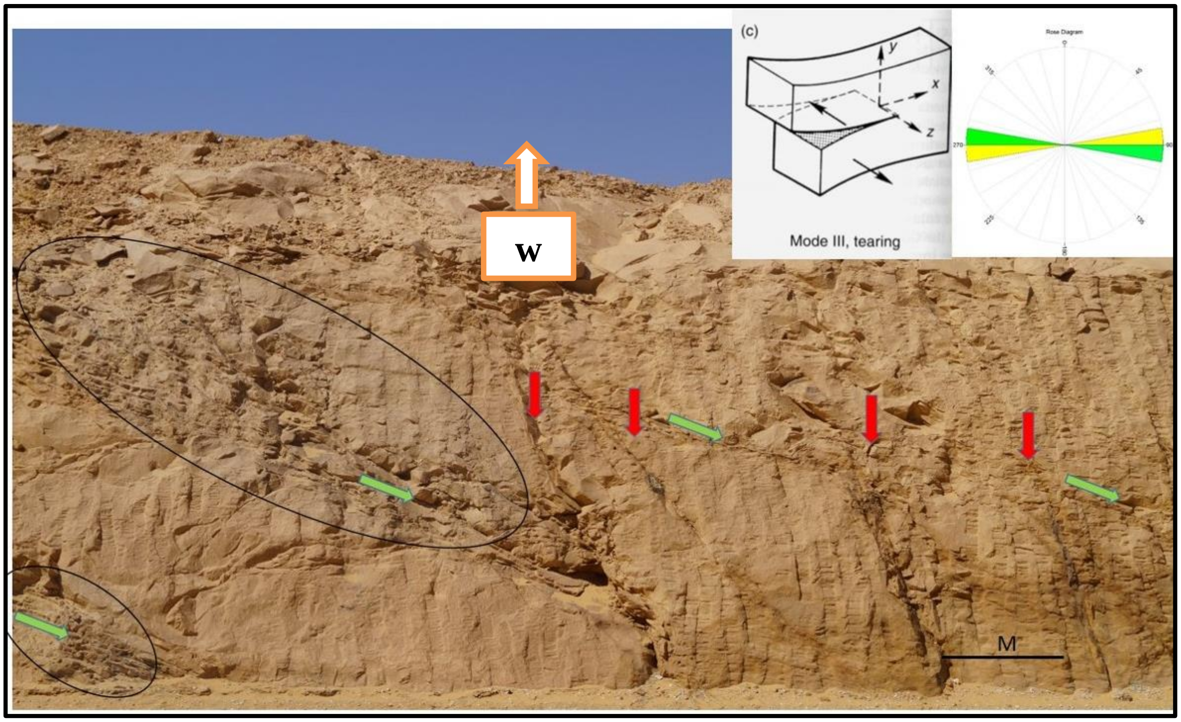

Figure 0.9 Shear fracture set (Mode III fracture set) E-W strike fracture sets at Sarah Paleochannel.

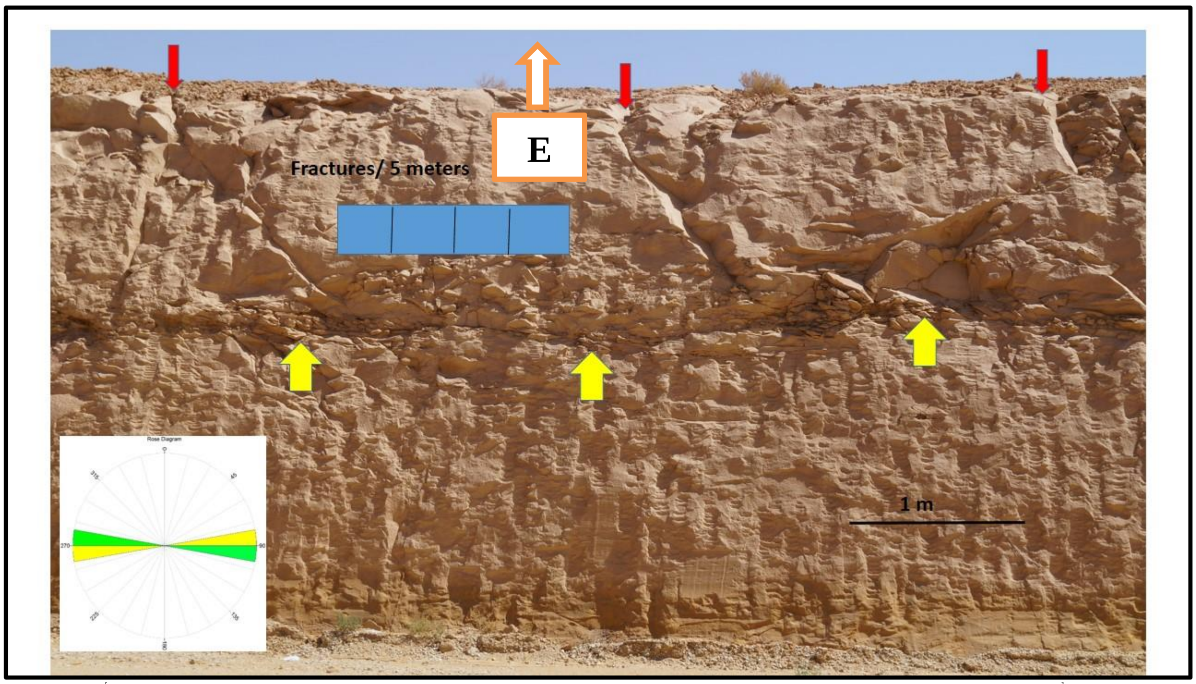

Figure 0.8 E-W strike fracture propagation in different lithologic units at Sarah Paleochannel

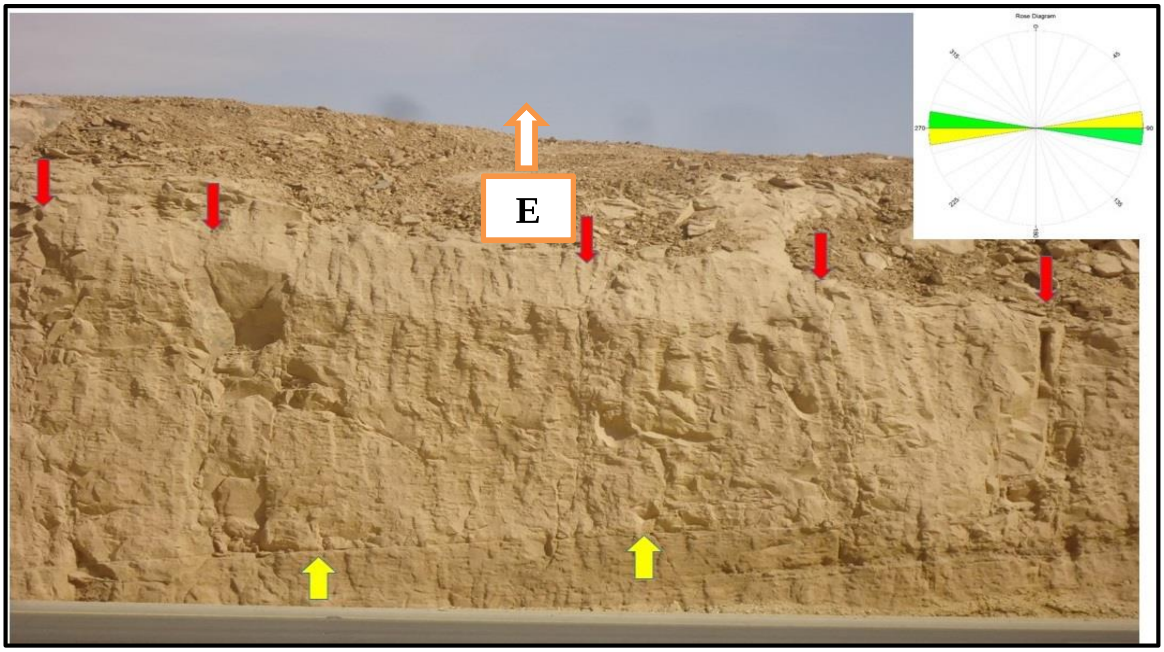

Figure 0.10 E-W strike fracture propagation in different lithologic units at Sarah Paleochannel

The top view of fracture describes three sets of fractures striking E-W, N-S and NW-SE direction appears at the cross sectional view of the Paleochannel.

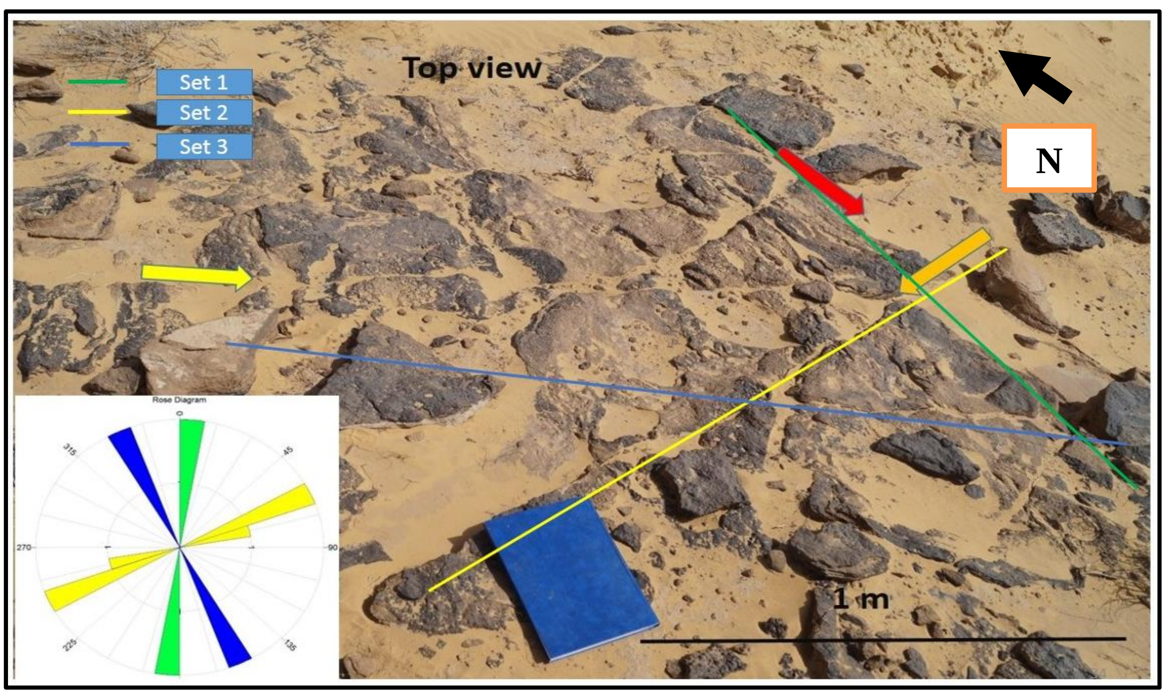

Figure 0.11 Top view the three sets of fractures indicated by colored lines at Sarah Paleochannel

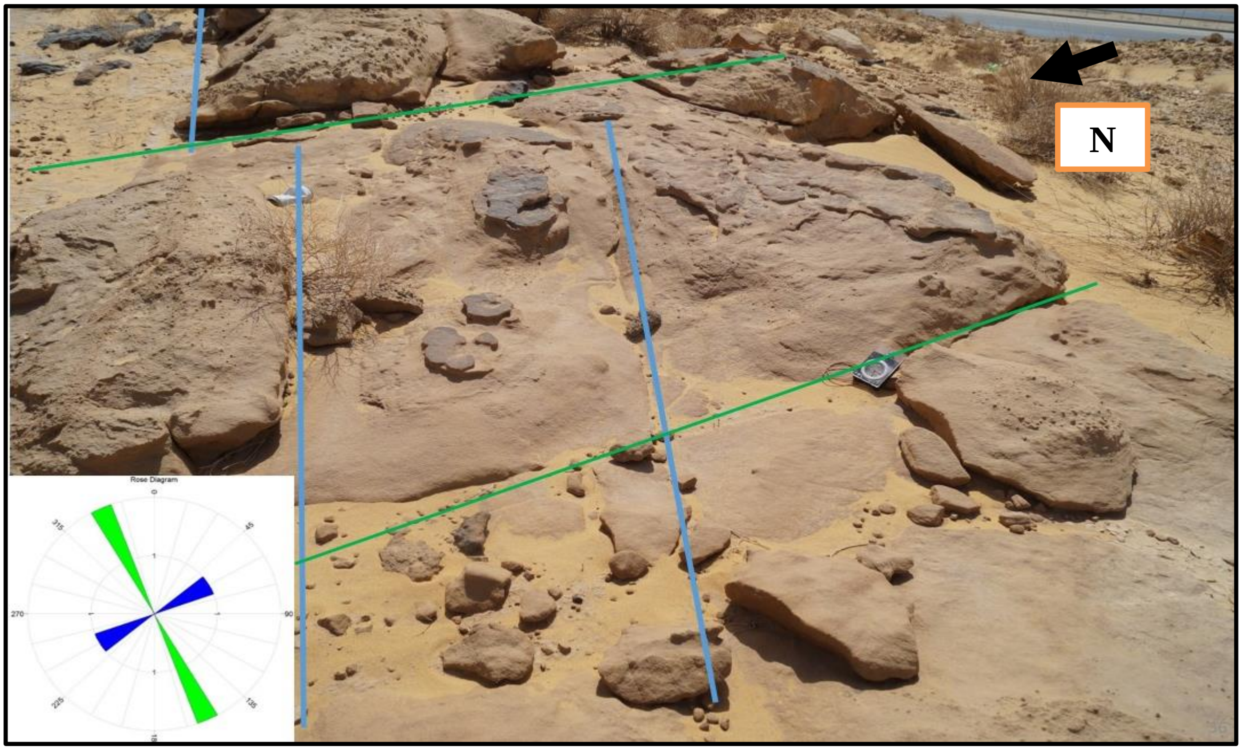

Figure 0.12 Top view the tow sets of fractures indicated by colored lines at Sarah Paleochannel

4.4 Fluid Barrier and fracture fill

Bukhamseen et al. (2010) established a successful fracture simulation model for Sarah tight gas reservoir in Rub Al-Khali Empty Quarter of Saudi Arabia. They investigated some geomechanical parameters such as modules and the fracture pattern from the FMI log. And found three type of fractures ranging between resistive, closed fracture to conductive, and open fracture. These subsurface results have been confirmed on the outcrop scale in Rawd Al-Jawa by the presence of three types of fractures, namely open fractures, closed shear fractures and resistive to closed fractures filled with gypsum. (Figure 4-13) shows a shear fracture considered as unconformity surface separating two types of sandstone packages and acting as a fluid barrier fluid movement. This type of shear fractures reduce the reservoir quality. The fractures filled with gypsum are also considered as fluid barriers and they reduce reservoir quality. The good porosity values and open fractures act positively to increase reservoir quality. All these fracture types occur~~s~~ in the sandstone lithofacies, which consists of sandstone packages from different origins separated by ferruginous surfaces In (Figure 4-14) the siltstone lithofacies and mudstone lithofacies decrease the reservoir quality because of their low permeability values but it can also act positively to increase reservoir quality by acting as a seal for the reservoir units. Ferrugination is considered one of the major factors in reducing reservoir quality. This ferruginous sandstone is distributed throughout sandstone lithofacies and on the top of the outcrop. Ferrugination occurs in irregular circular shapes on the outcrop, characterized by different sandstone composition inside and outside the ferruginous boundary and it is probably due to the concentration of iron oxide and iron rich grains and/or cement and the movement of irons in aqueous condition. This ferruginous boundary has a thickness from 2 to 7 cm characterized by the absence of porosity and permeability and occurring in irregular circular shapes from a few centimeters to more than one meter length.

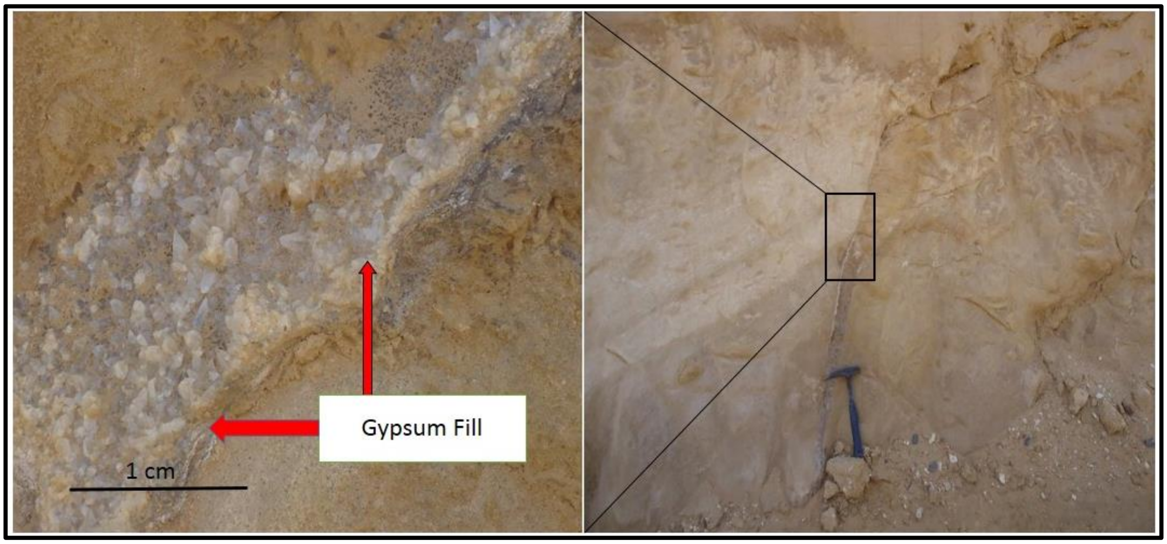

Figure 0.14 Fracture fill with digenetic gypsum (resistive fracture) at Sarah paleovalley

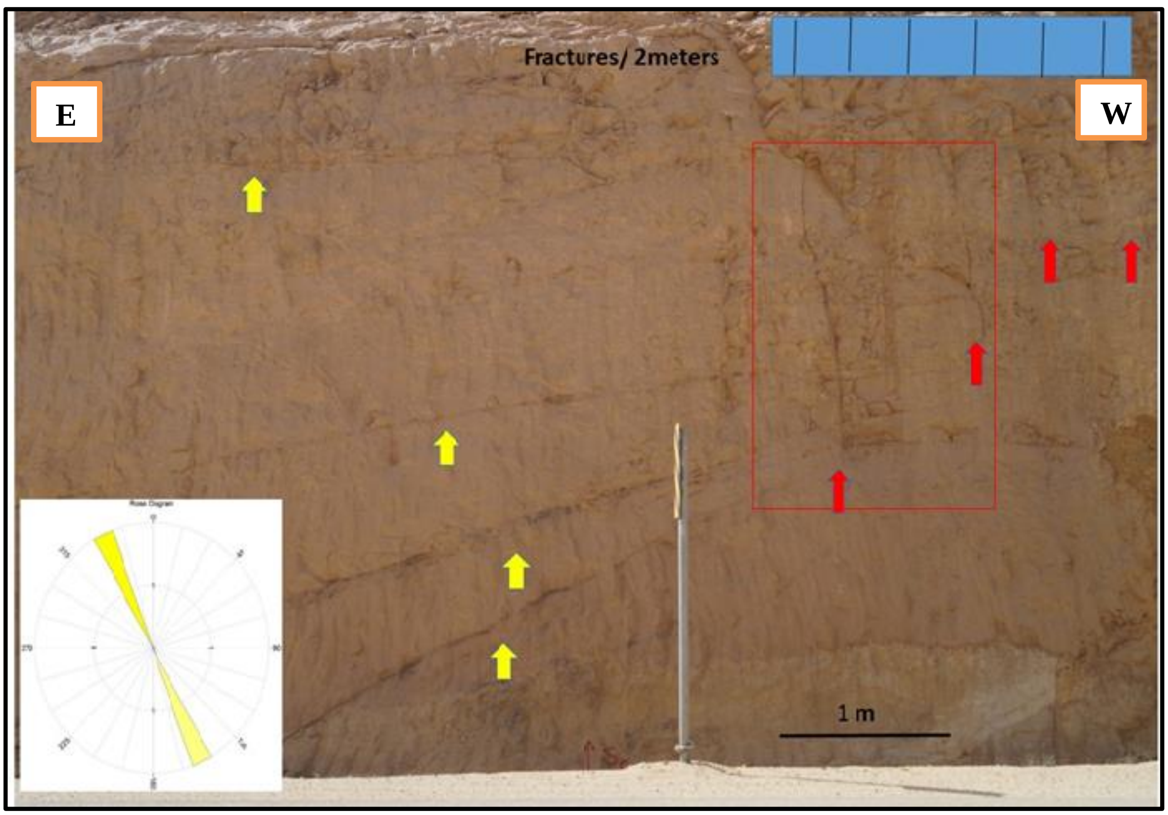

Figure 0.13 Fracture fill with iron oxides and opened fractures (open and closed fractures) at Sarah paleovalley.

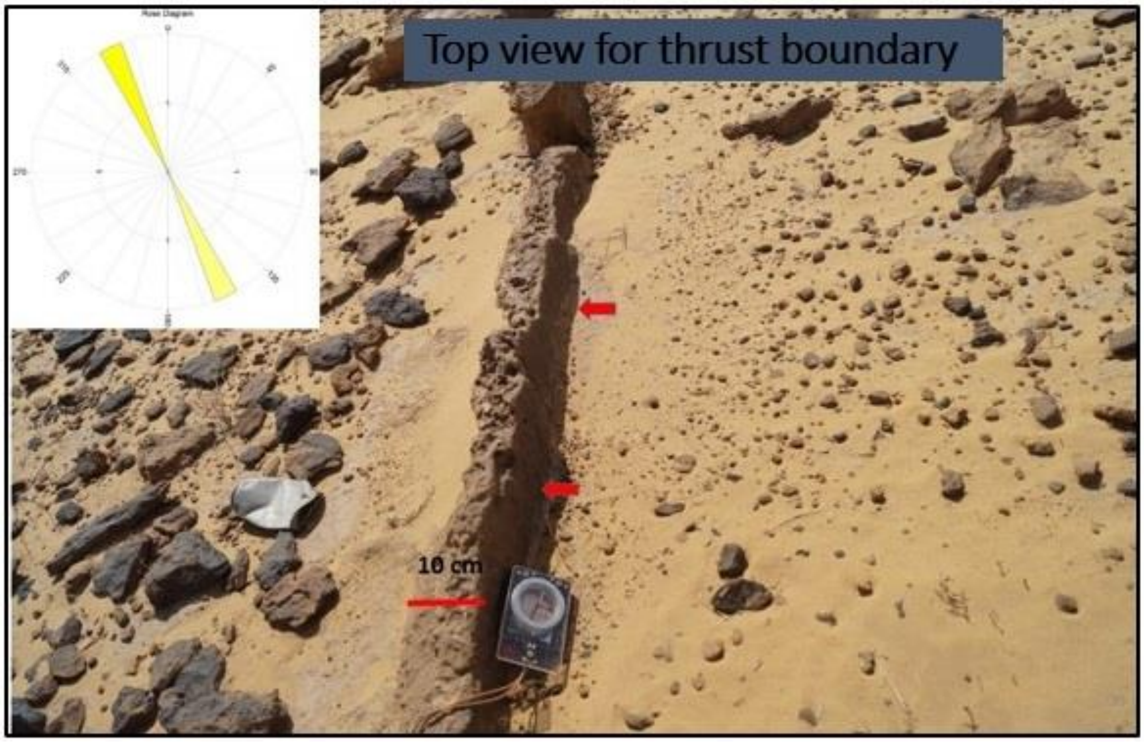

Figure 0.16 Top view for thrust fracture filled with iron oxides (fluid barrier)

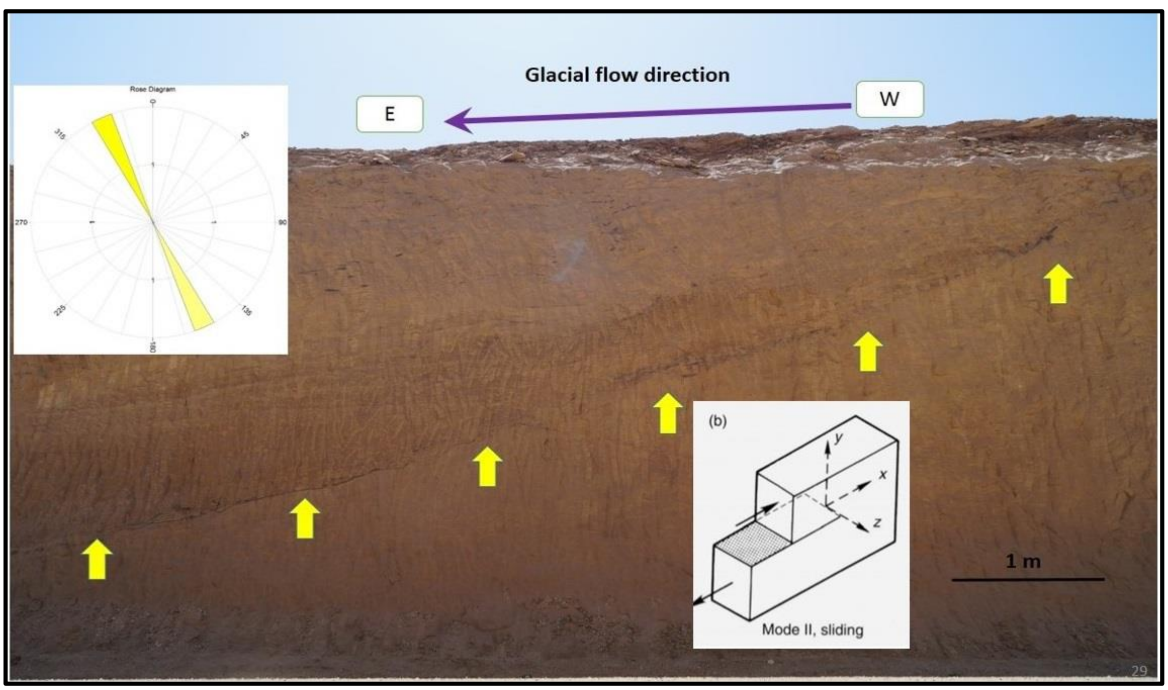

Figure 0.15 Thrust fracture filled with iron oxides separate different glacial event (fluid barrier)

The fracture orientations coincide with those of Bukhamseen et al.|(2010) fracture simulation model for Sarah tight gas reservoir in the subsurface. They also describe three types of fractures fill ranging between resistive, closed fracture to conductive, and open fracture. The conductivity of fractures and fractures fill described by Bukhamseen et al.|(2010) without explanation to the type of fractures fill. This study overcome this limitation in Bukhamseen et al.|(2010) work. The resistive fractures probably represent the fractures filled with gypsum while the closed fractures are mainly filled with iron oxides. According to the fractures orientation and fractures fill in Bukhamseen et al.|(2010) work, the studied fracture at the study area can be correlated to the subsurface fractures. The fracture model created which describe the fracture characteristics, orientations (figure 4-17) and the relation between the fractures propagation and lithologic characteristics.

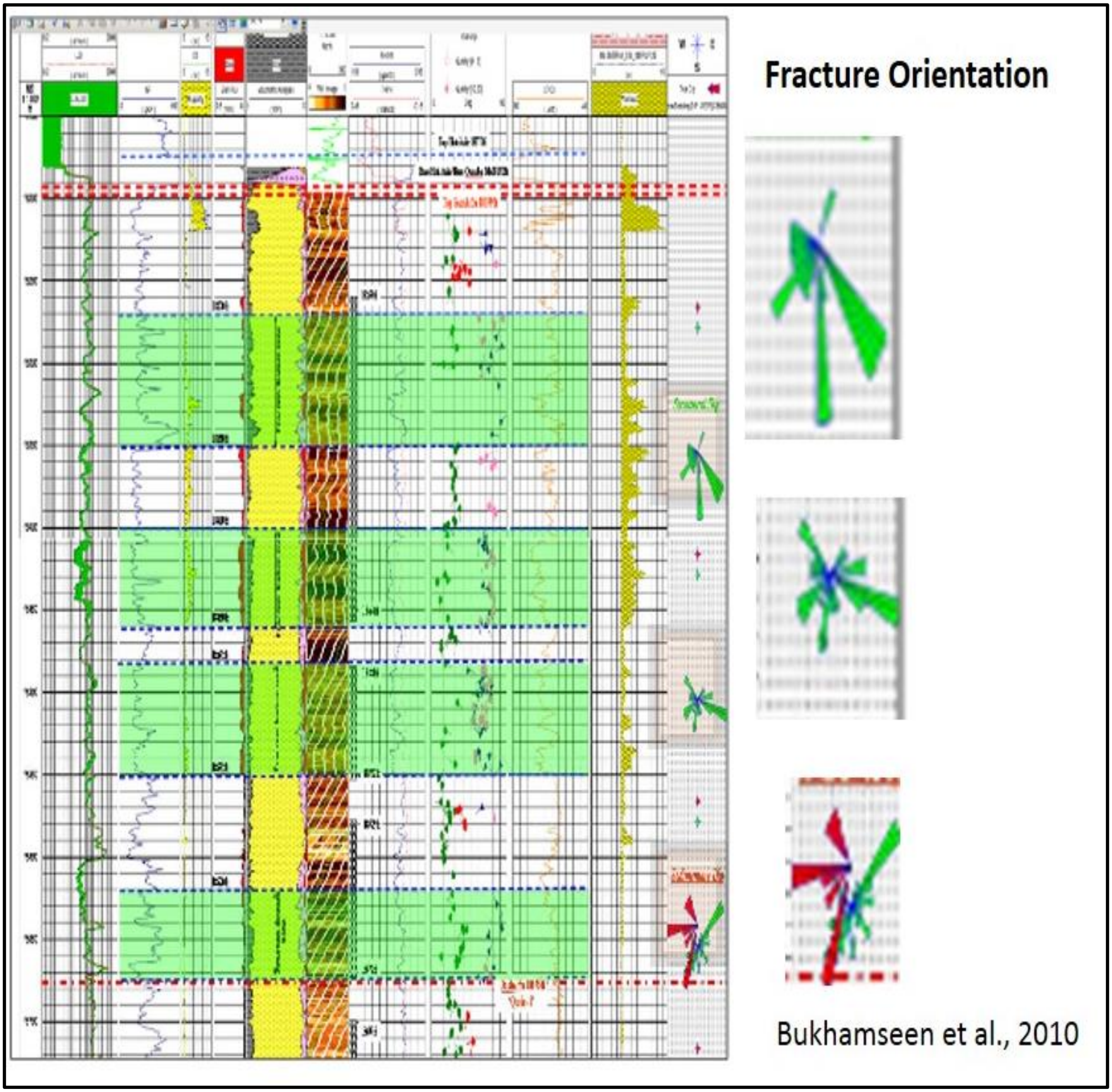

Figure 0.17 Fracture zones and orientations for Sarah reservoir Bukhamseen et al. (2010)

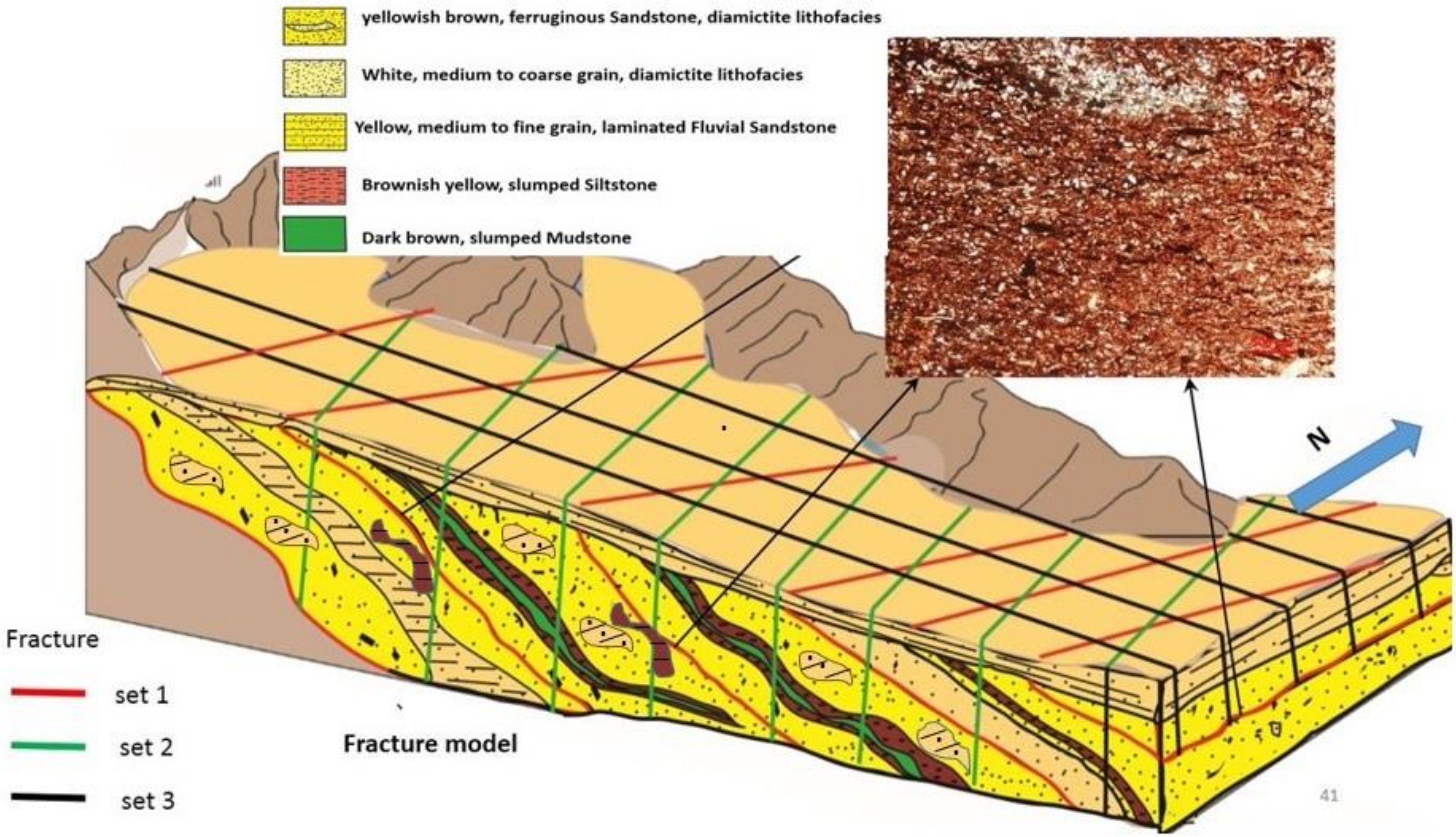

Figure 0.18 Fracture and lithological model for Sarah Paleochannel describe the relation between fracture propagation and lithologic units. The vertical and horizontal heterogeneity of lithology associated with structure heterogeneity. The thin section for the thrust boundary fracture fill (iron oxides).

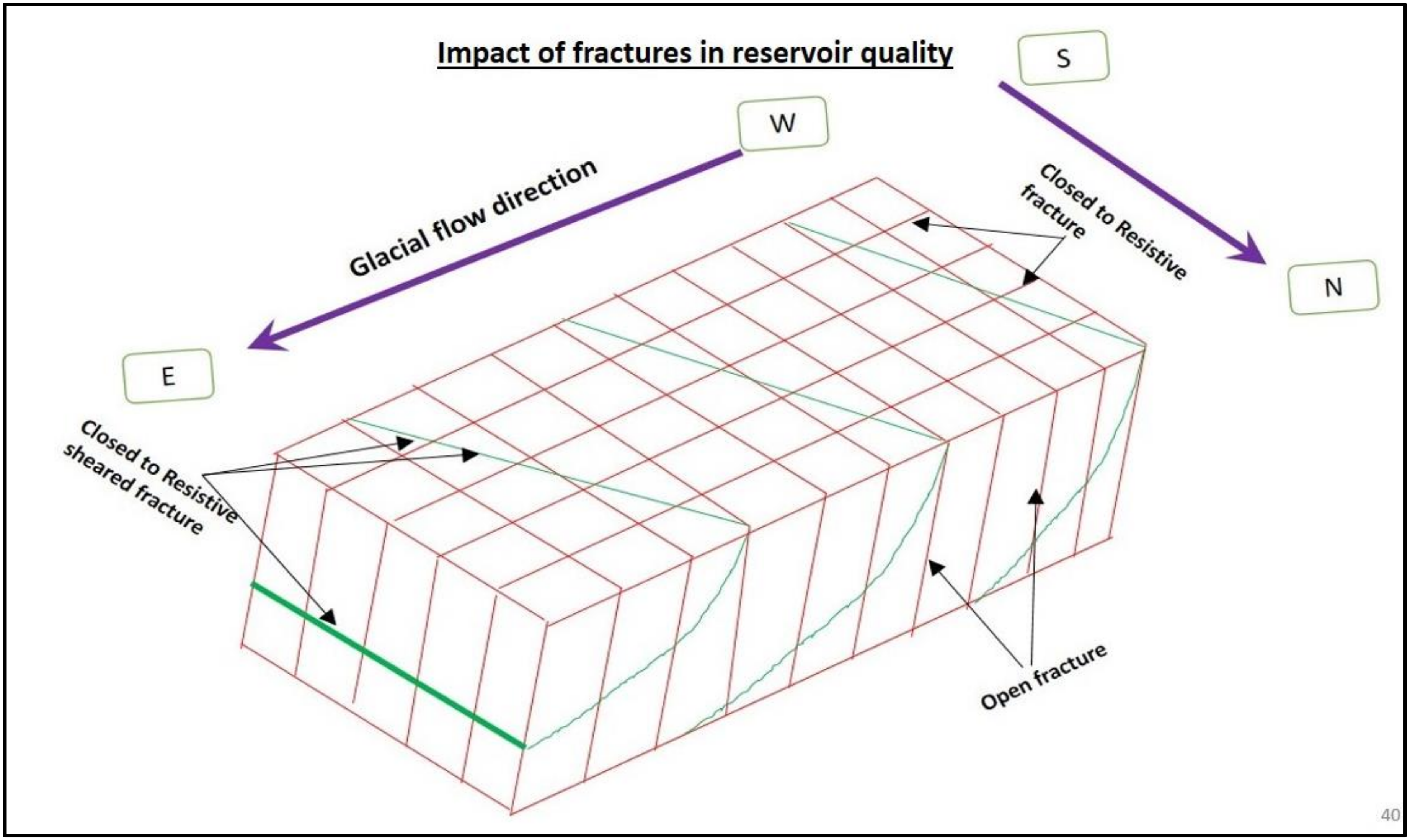

Figure 0.19 Sketch describes fractures orientation and characteristics at Sarah Paleochannel

CHAPTER 5

The Relationship between LithoStratigraphy and Geomechanical Properties

5.1 Introduction

The study of the relationship between lithostratigraphy and geomechanical properties will lead to understand the nature and quality of the reservoir units and to identify the attributes affect the reservoir units. To find relations between stratigraphical and geomecahical properties for a reservoir requires to identify stratigraphical and geomechanical units, relations between them and to study the impact of heterogeneity throughout those units. The geomechanical unit identified as a single unit has the same intensity of deformation and the same mechanical properties. Nelson, (1985) describes the difference between geomechanical units based on subtle changes in petrophysical properties. One of the major factors in geomechanical unit is the intensity of fracturing which change from one unit to another. There is strong relation between lithology and fracture intensity, which can used as a link between lithostratigraphical and geomechanical units. (Gross, 1993) defines the relation between geomechanical unit and lithostratigraphic unit as a geomechanical layer, which may have one or more lithologic units all having the same response to applied stress. The outcrop in the study area is expressed as a set of different lithological layers subjected to stresses. The lithostratigraphic units gave different responses to the stress applied to the paleovalley units as can be concluded by the presence of slumped lithologic layers, folding and fractures. The behavior of a lithologic unit subjected to stress might range from ductile behavior in one lithologic unit to brittle behavior in other units, which reflects different geomechanical behavior for the different lithological units. In this chapter I study the relationship between lithostratigraphy and geomechanical properties of units by analyzing their lithological and petrophysical characteristics and integrate the results to define the relation between lithologic and geomechanical units.

5.2 Lithologic Unit

The outcrop of the study area is characterized by glacial and glacio-fluvial sediments evidenced by the presence of big boulders (1 to 5 m) of diamictite, which suggests heterogeneous reservoir properties vertically and horizontally. The locations of vertical sections (Figure 4.2) encompasses most of the lithofacies occurring in the study area. Therefore, the mechanical characteristics will represent most of the mechanical units in the outcrop location.

Figure 5.1 Photograph for the locations of stratigraphic sections

The vertical stratigraphic units for the studied sections were divided into genetically related units having the same sedimentological characteristic in terms of lithology, porosity and permeability.

5.3 Stratigraphic Section

The stratigraphic sections describe five lithofacies which are (i) yellowish brown, poorly sorted, medium to coarse, diamictite texture, ferruginous sandstone lithofacies, (ii) white, medium to coarse grain, diamictite texture, poorly sorted sandstone lithofacies, (iii) yellow, medium to fine grain, moderately sorted, laminated fluvial sandstone lithofacies, (iv) brownish yellow, finely interbedded, slumped siltstone lithofacies and (v) dark brown, slumped mudstone.

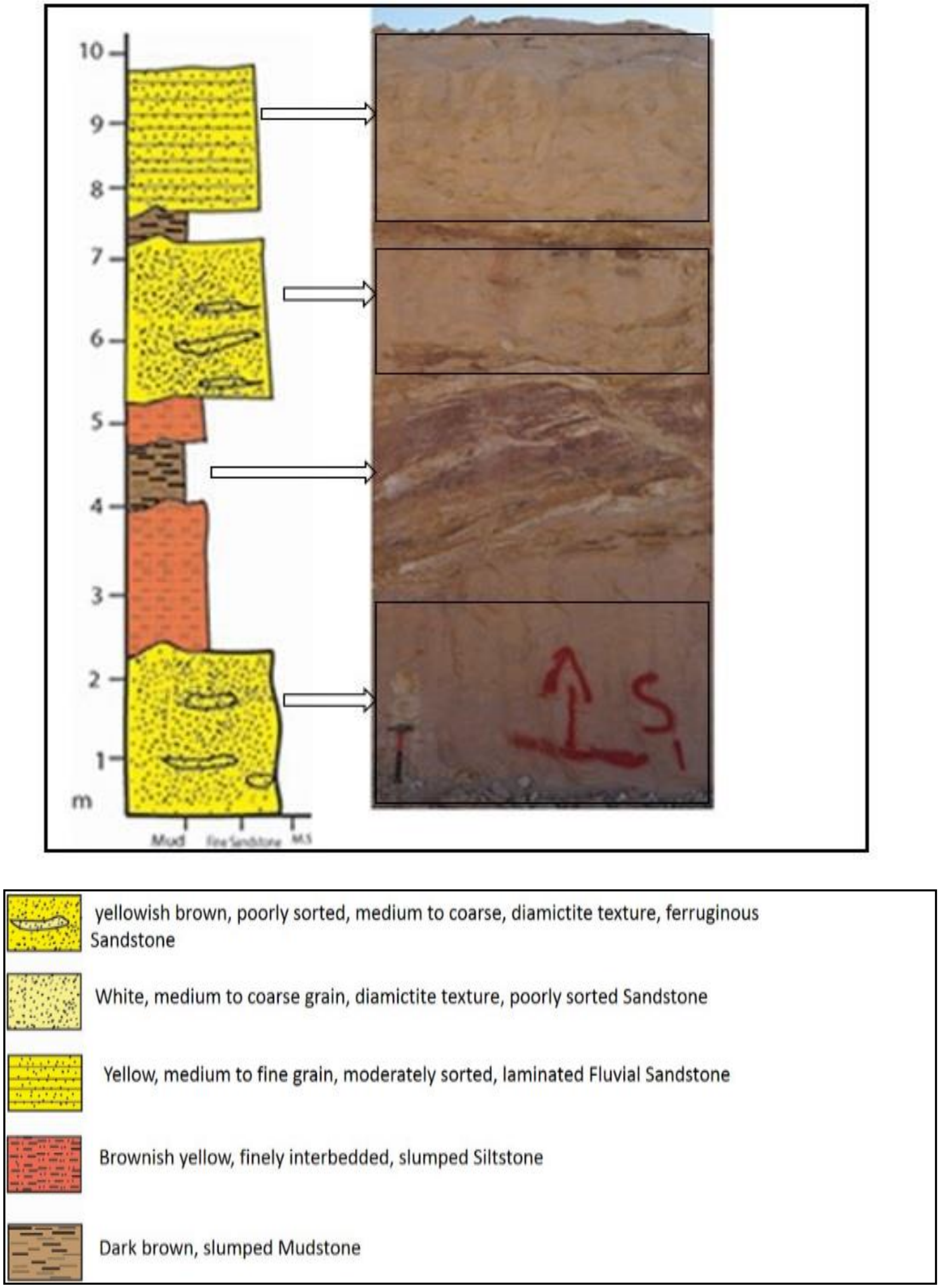

Figure 5.1 The vertical stratigraphic section for location 1

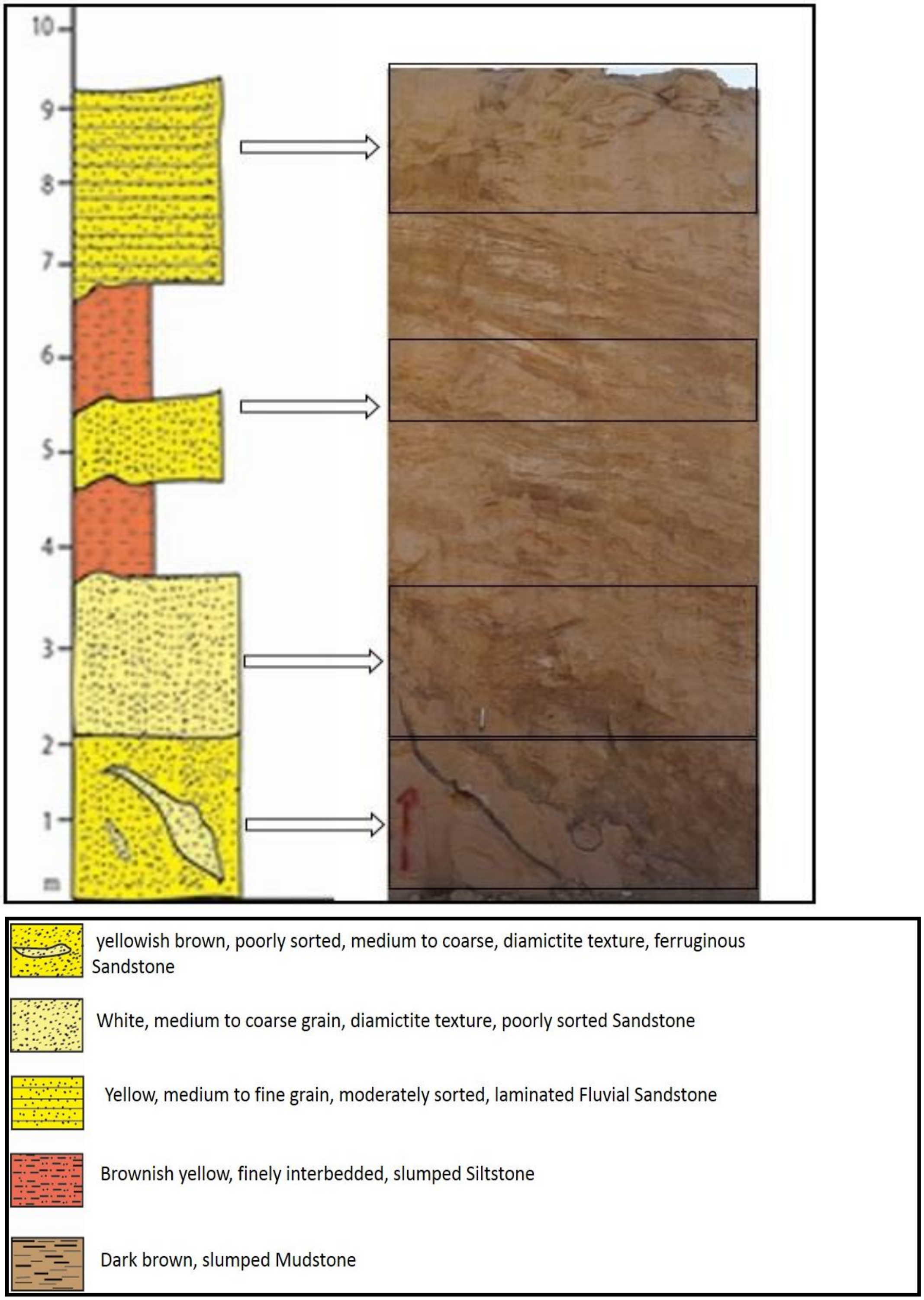

Figure 5.2 The vertical stratigraphic section for location 2.

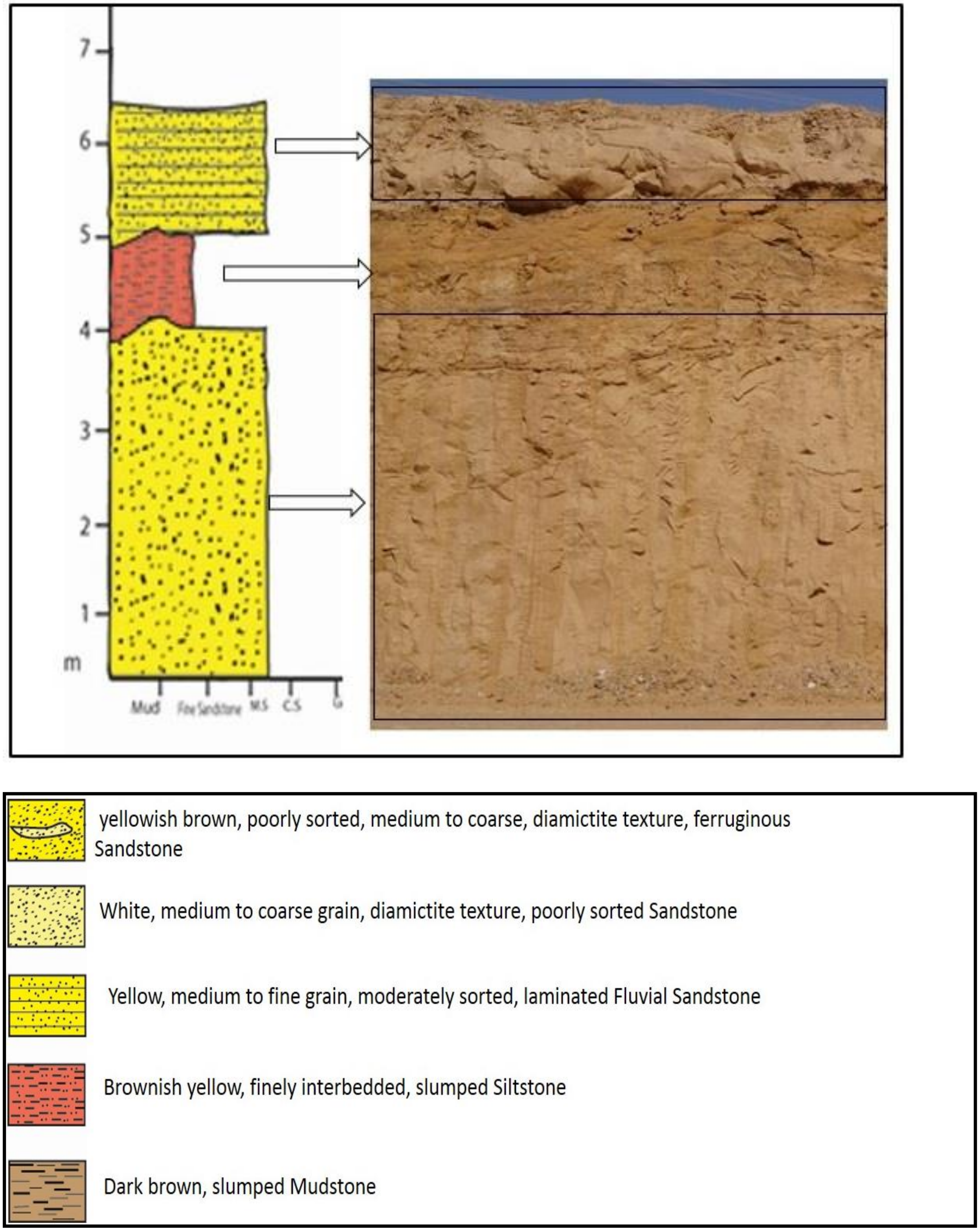

Figure 5.3 : The vertical stratigraphic section for location 3.

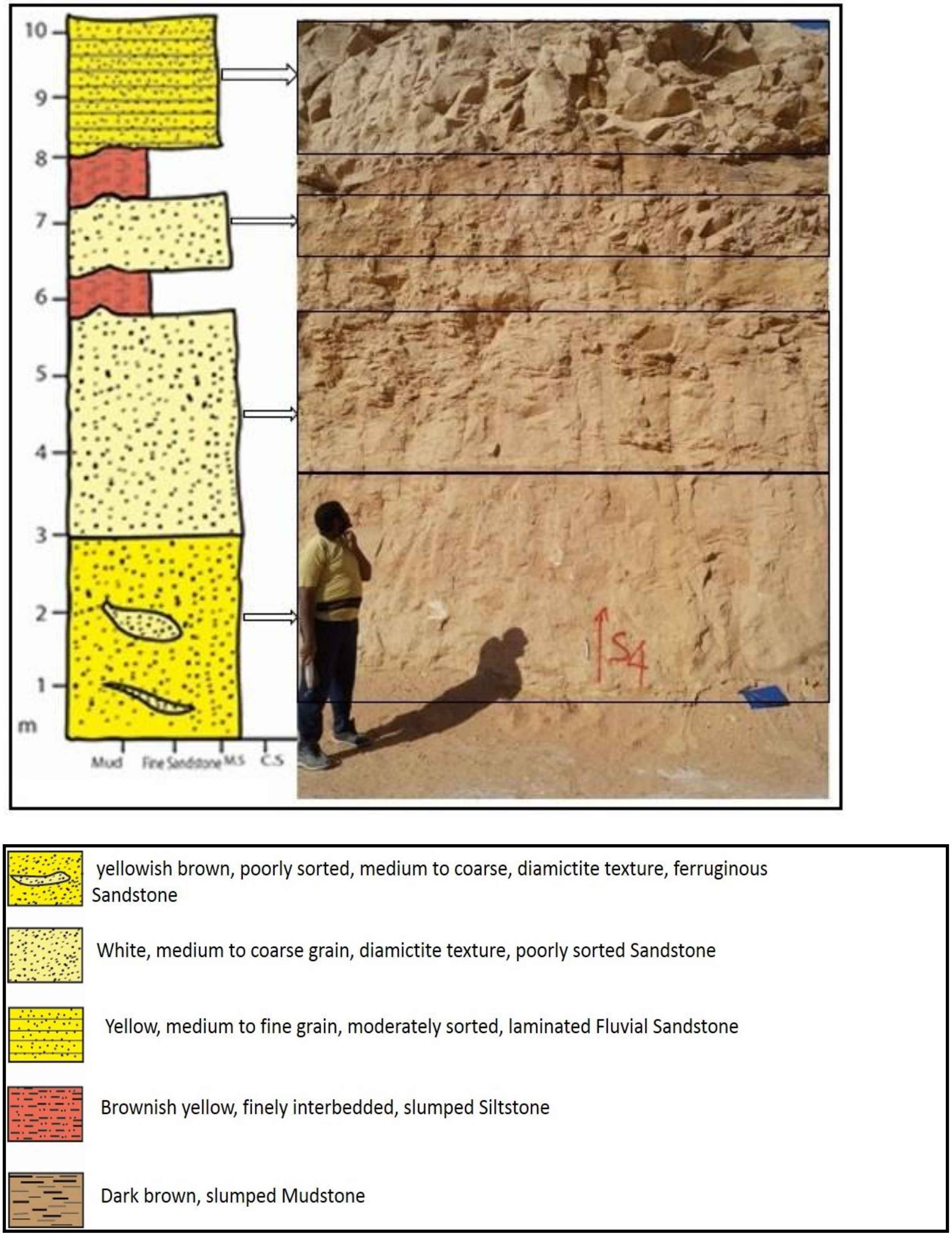

Figure 5.4 The vertical stratigraphic section for location 4.

The vertical section of the outcrop was sampled every 40 cm approximately and measurements were also taken in the sample locations. Spectral gamma ray readings were also taken for the vertical sections at each sample locations and integrated with Schmidt hammer measurements. The vertical plots below show the spectral gamma ray, Schmidt hammer average and point load average for section 1. The repetitive pattern in gamma ray identical lithologic content. This measurement was conducted for the four outcrops to define the response of the lithologic units to geomechanical tests.

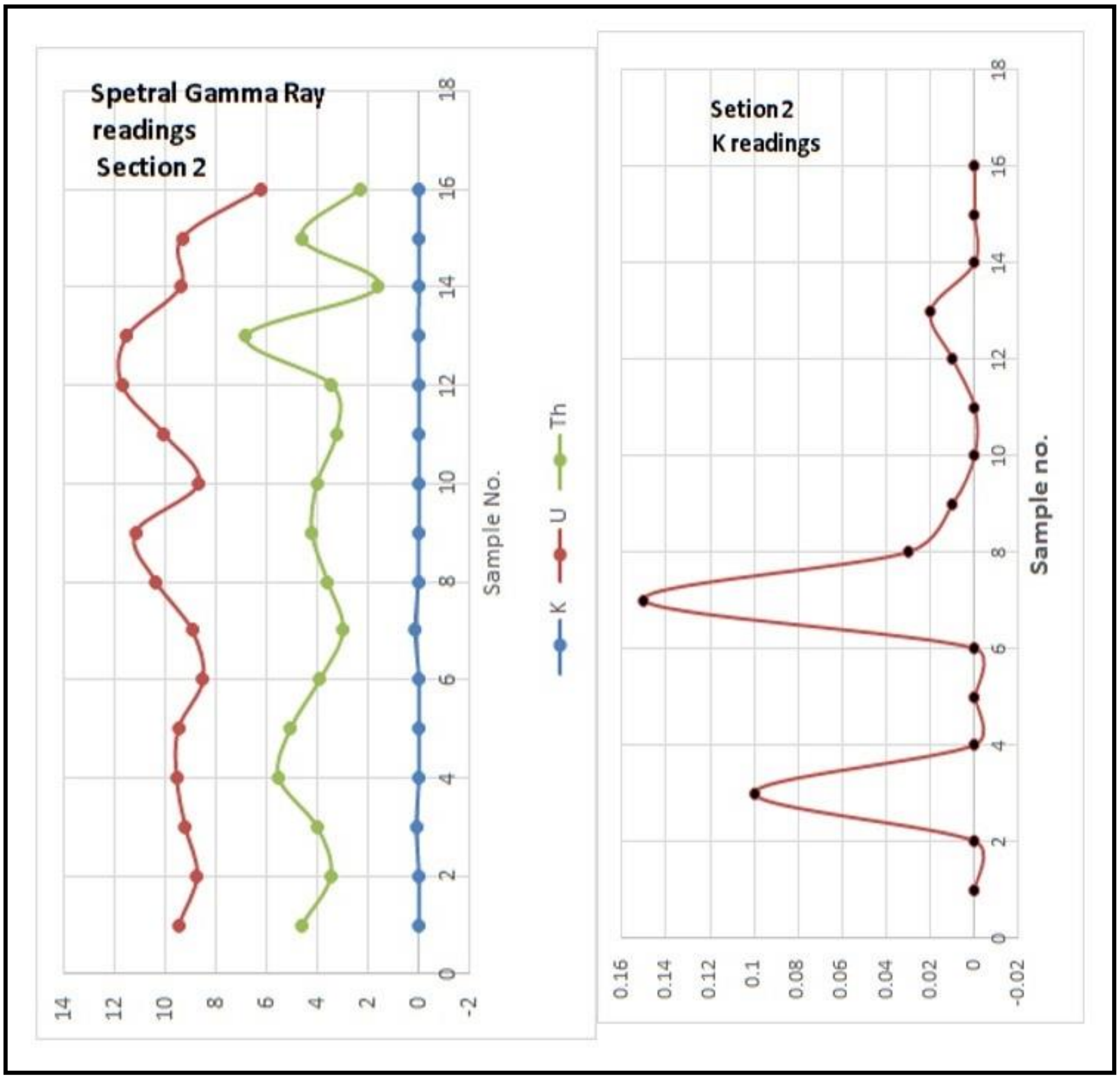

Figure 5.5 Vertical spectral gamma ray plots at Sarah paleochannel for section 1

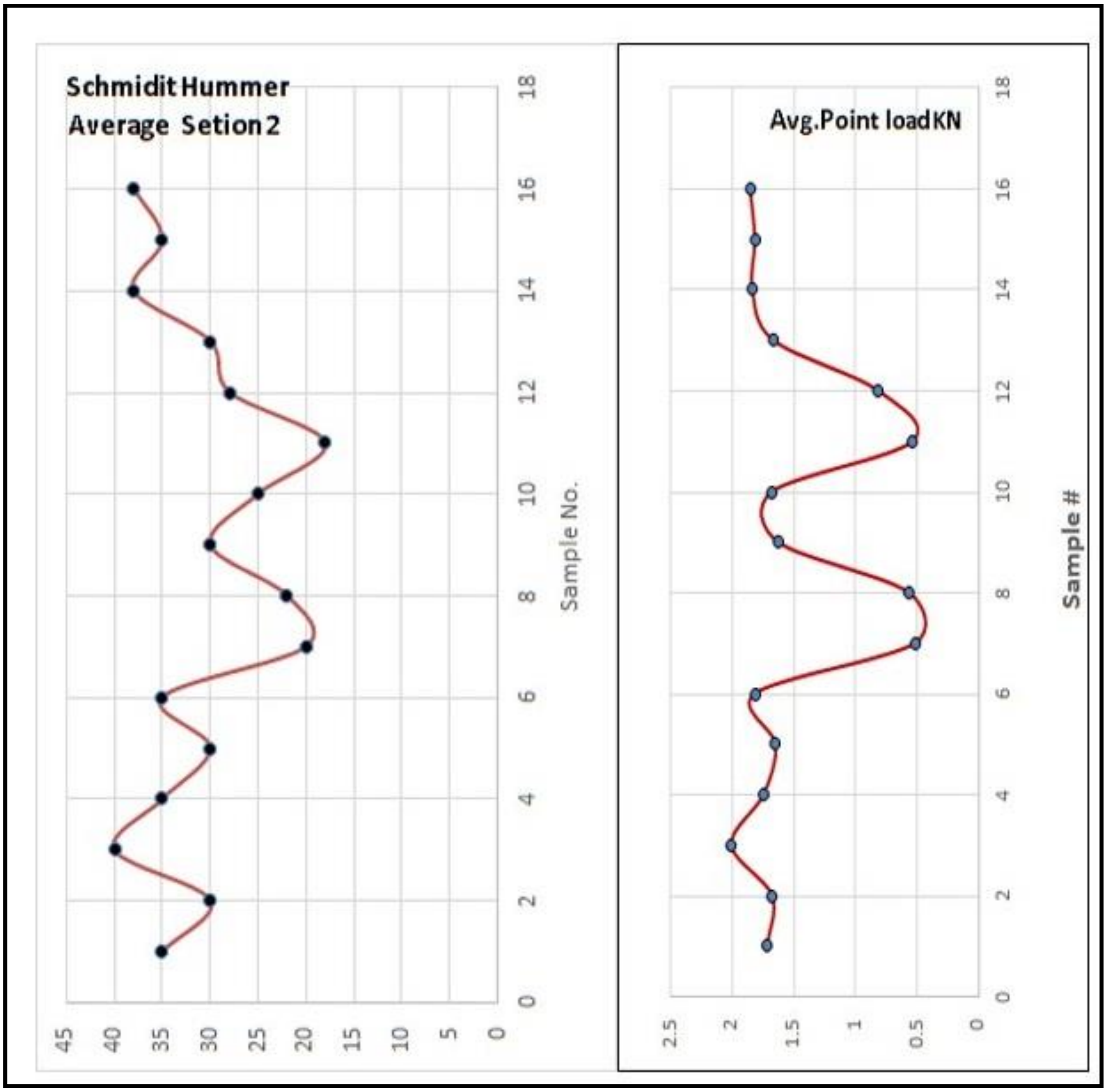

Figure 5.6 Vertical Schmidt hammer average and point load average plots for section 1 at Sarah paleochannel.

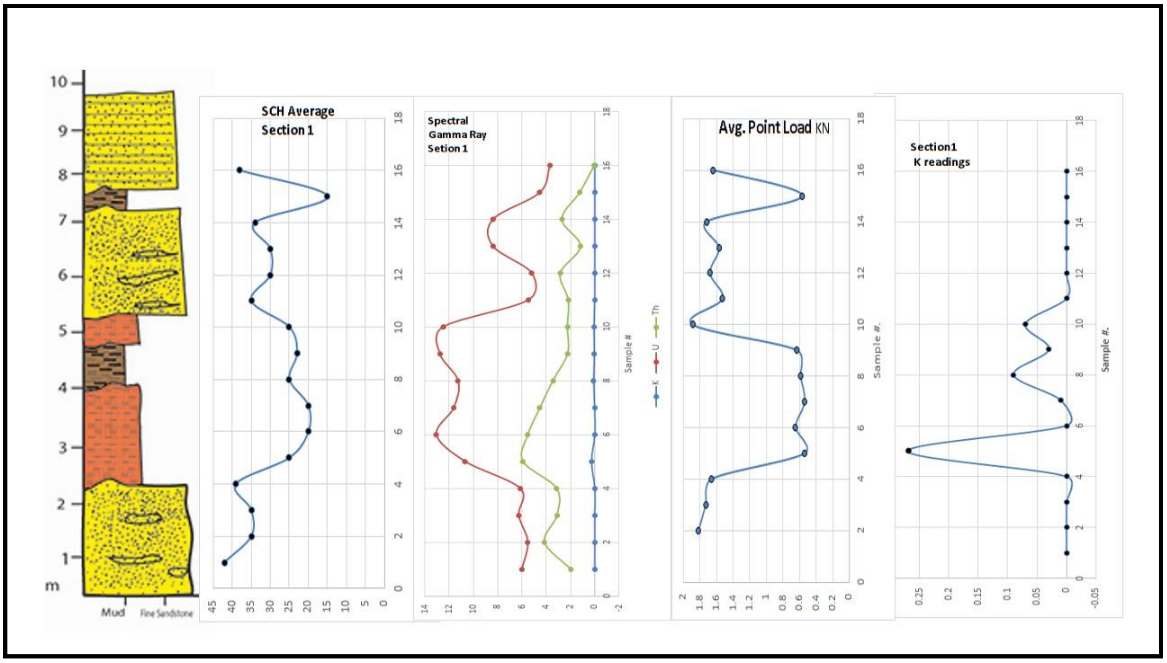

Figure 5.7 Vertical section for location1 with vertical spectral gamma ray readings, Schmidt hammer average and point load average readings at Sarah paleochannel.1

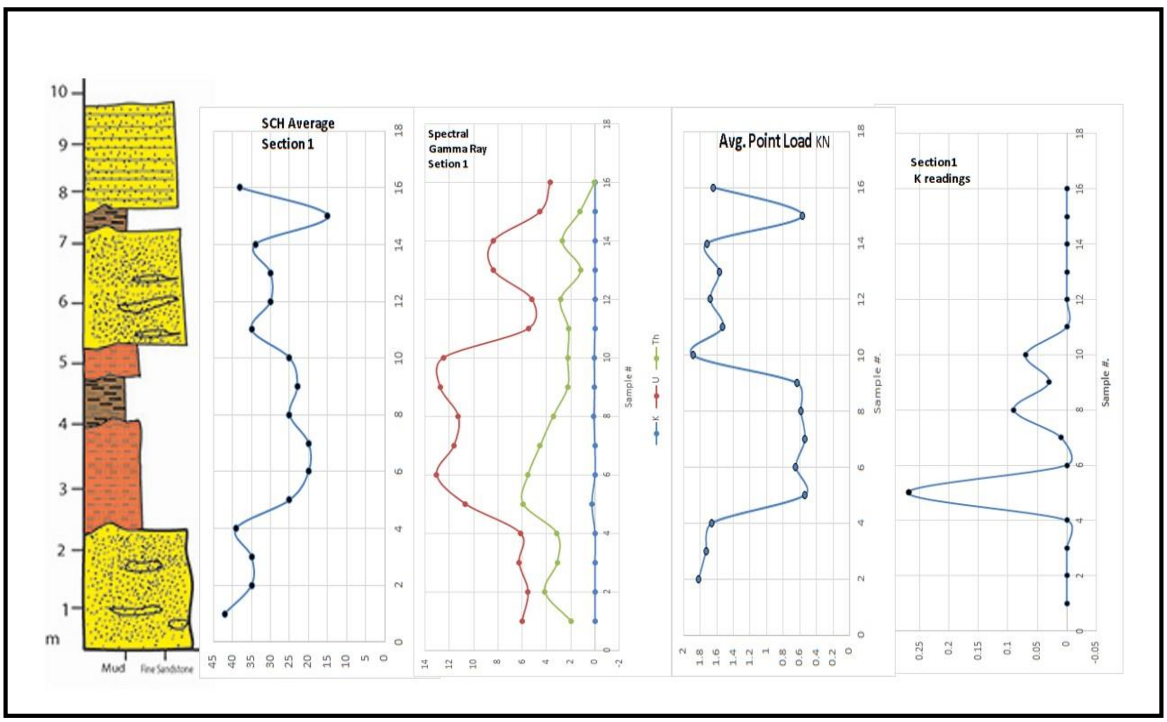

Figure 5.8 Vertical section for location 2 with vertical spectral gamma ray readings, Schmidt hummer average and point load average readings at Sarah paleochannel 1

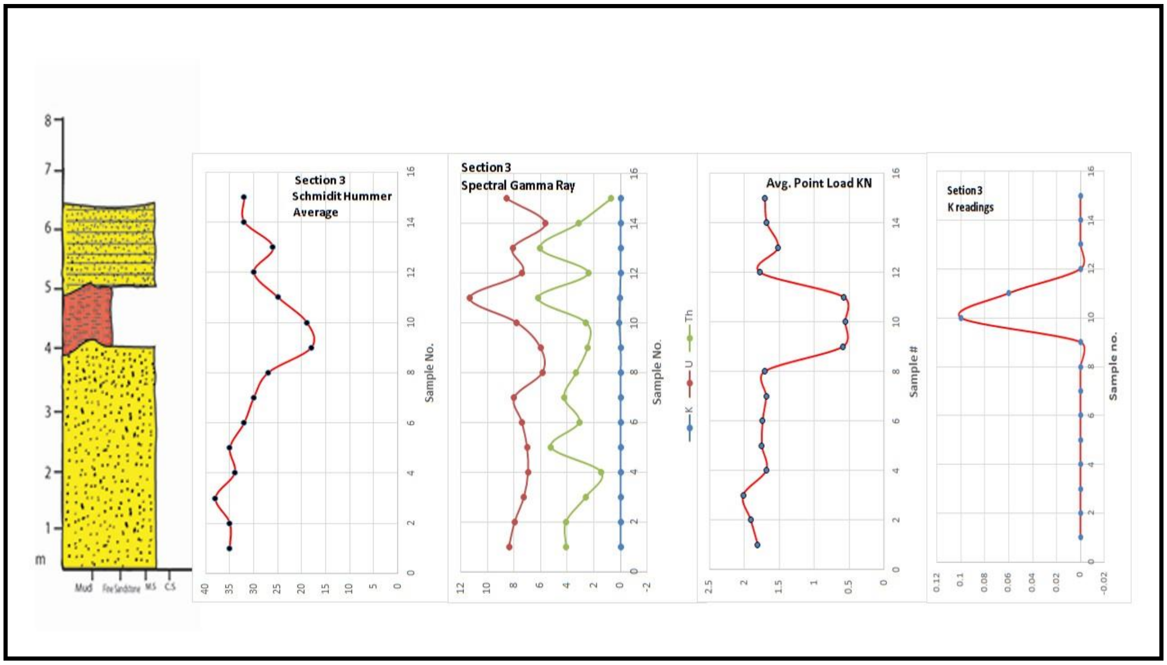

Figure 5.9 Vertical section for location 3 with vertical spectral gamma ray readings, Schmidt hammer average and point load average readings 1

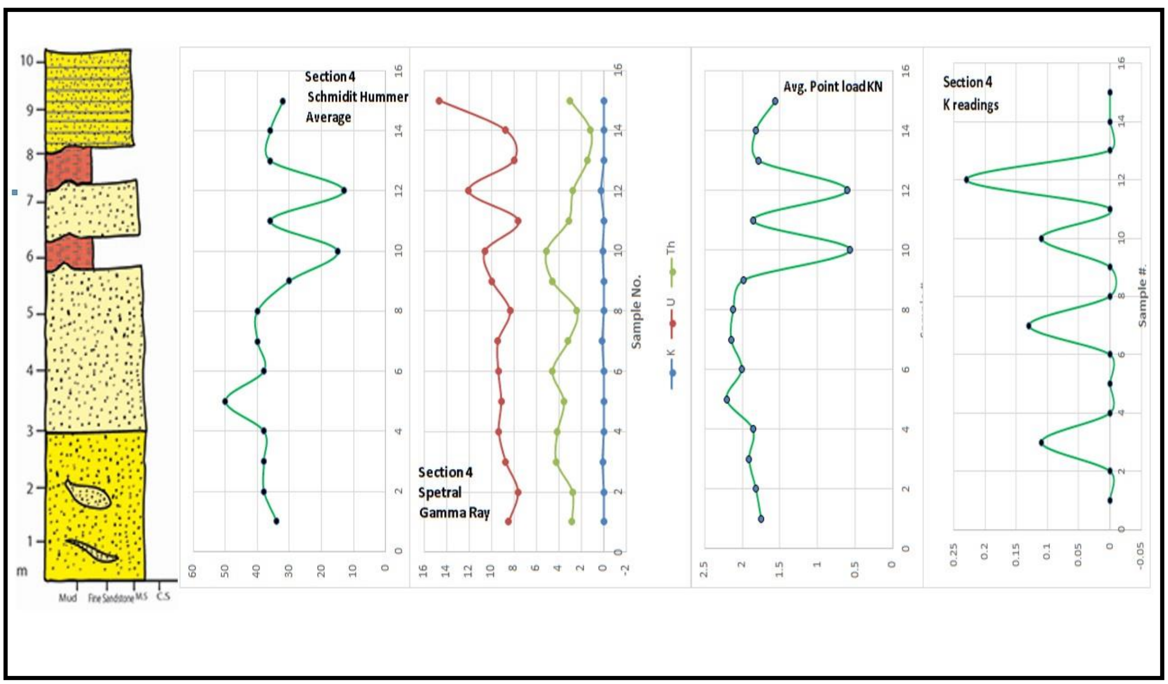

Figure 5.10 Vertical section for location 4 with vertical spectral gamma ray readings, Schmidt hammer average and point load average at Sarah paleochannel 1

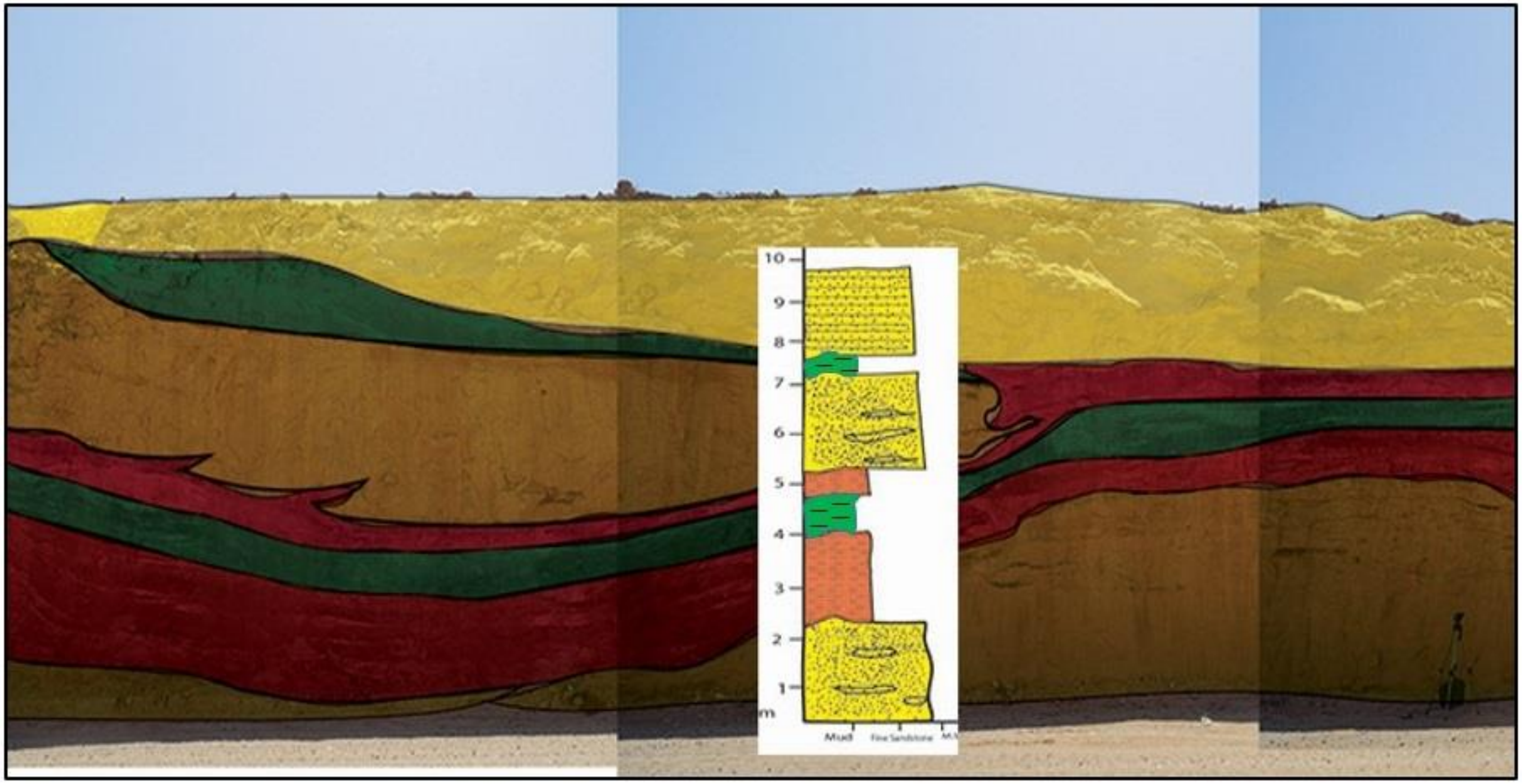

Figure 5.11 Photograph for sections 1 location and lithologic interpretation at Sarah paleochannel.

Figure 5.12 Photograph for sections 1 and 2 location and lithologic heterogeneity at Sarah paleochannel

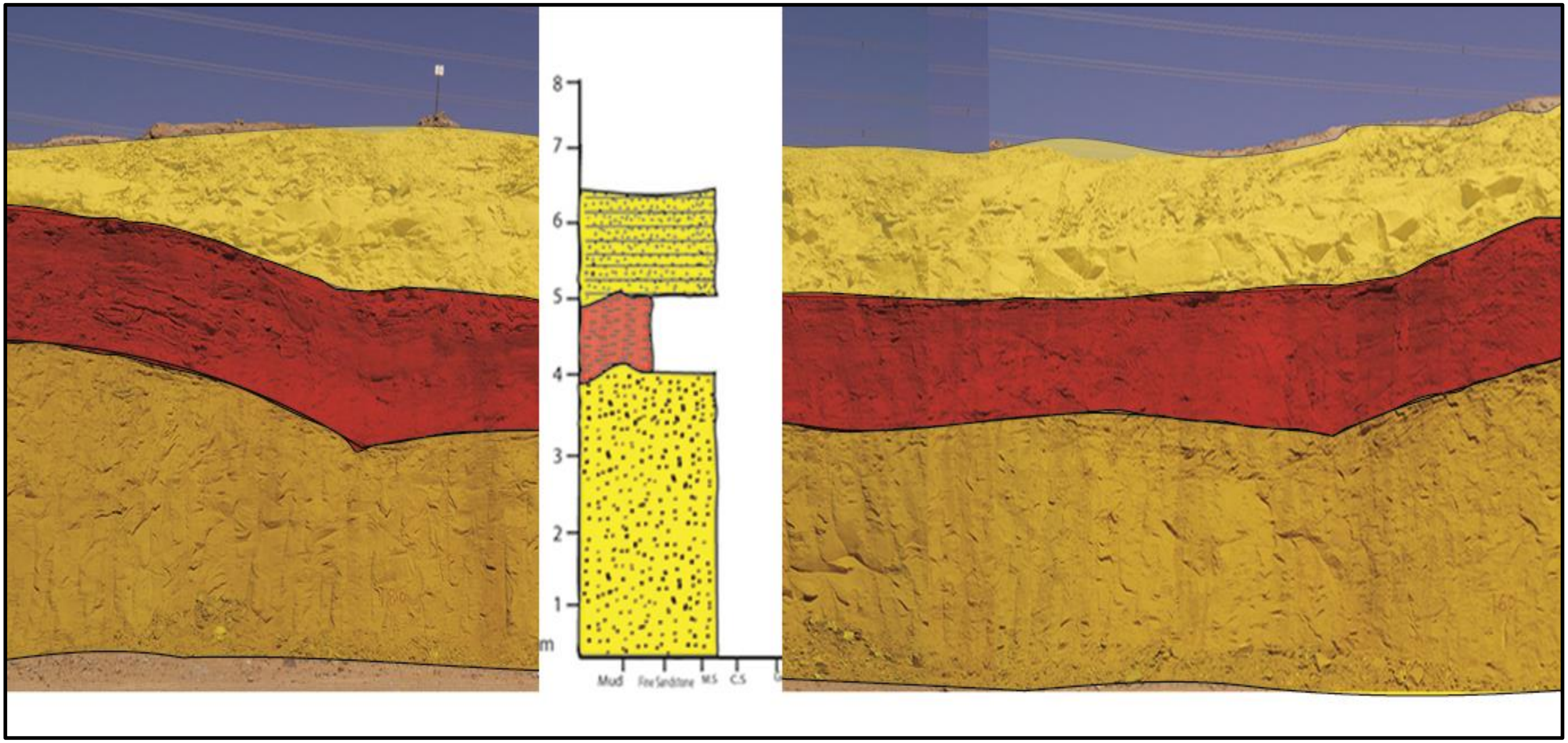

Figure 5.13 Photograph for sections 3 lithologic heterogeneity at Sarah paleochannel

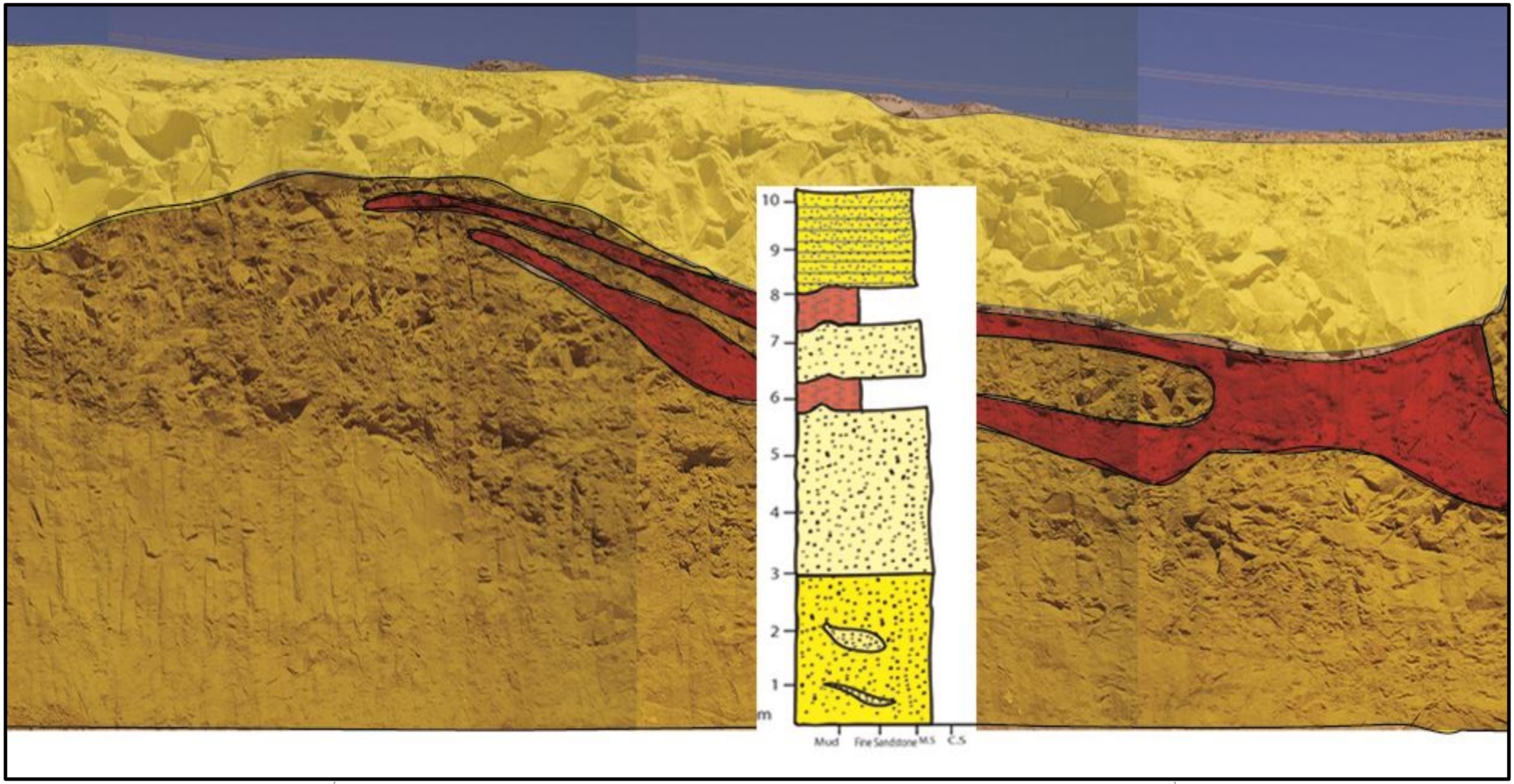

Figure 5.14 Photograph for sections 4 location and lithologic heterogeneity at Sarah paleochannel

5.4 Petrophysical Properties

One of the major factors affecting petrophysical properties is the porosity, which is defined according to Duncan (1969) as the ratio of volume of voids to the total volume. Therefore, it depends on the density, compaction and the grain size distribution. The presence of pores in the sample decreases the strength of the samples. Therefore, there is a strong relation between mechanical properties and porosity as it appears clearly in the cross-plots below (Figure 5-16).

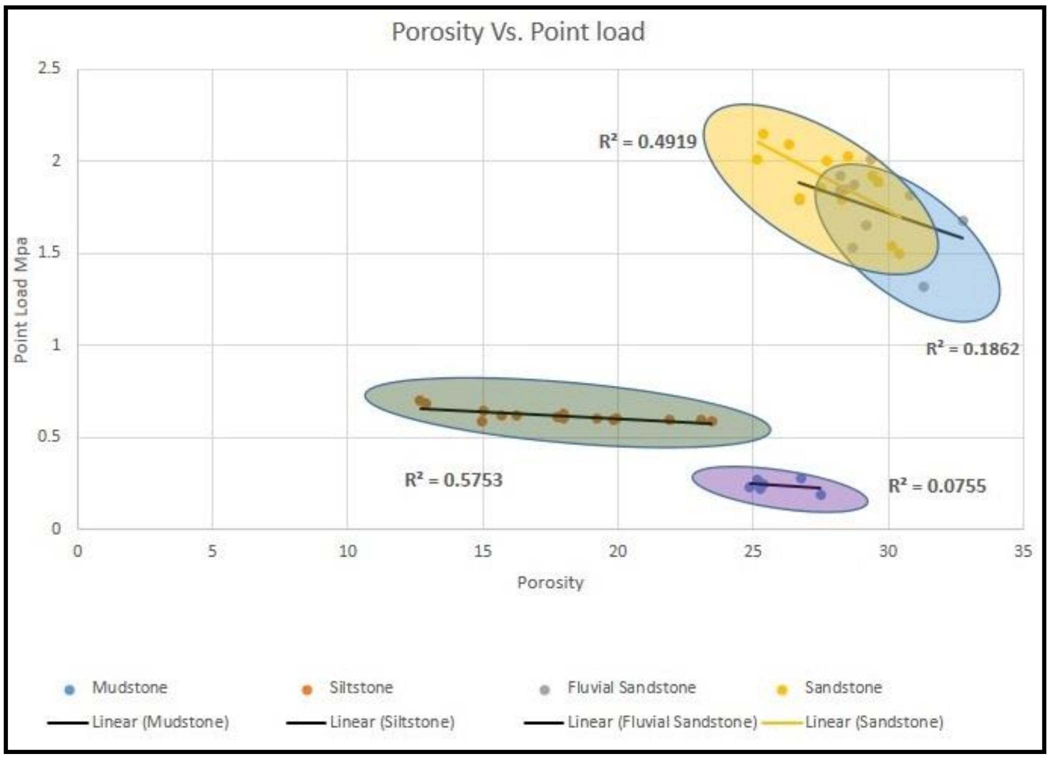

Figure 5.15 Scatter graph showing the relation between porosity and point load index. R2 measures the goodness of the linear regressions.

The cross plot illustrates the relation between point load index and porosity values for the lithofacies. The inverse relationship in the cross plot confirms rock strength decreases with increasing volume of the pores in the samples. The grouping in the cross plot reflects the differences between geomechanical and petrophysical properties for the various lithofacies in the outcrop. The cross-plot can divided to four main lithofacies domains, which are mudstone, siltstone, sandstone and fluvial sandstone lithofacies.

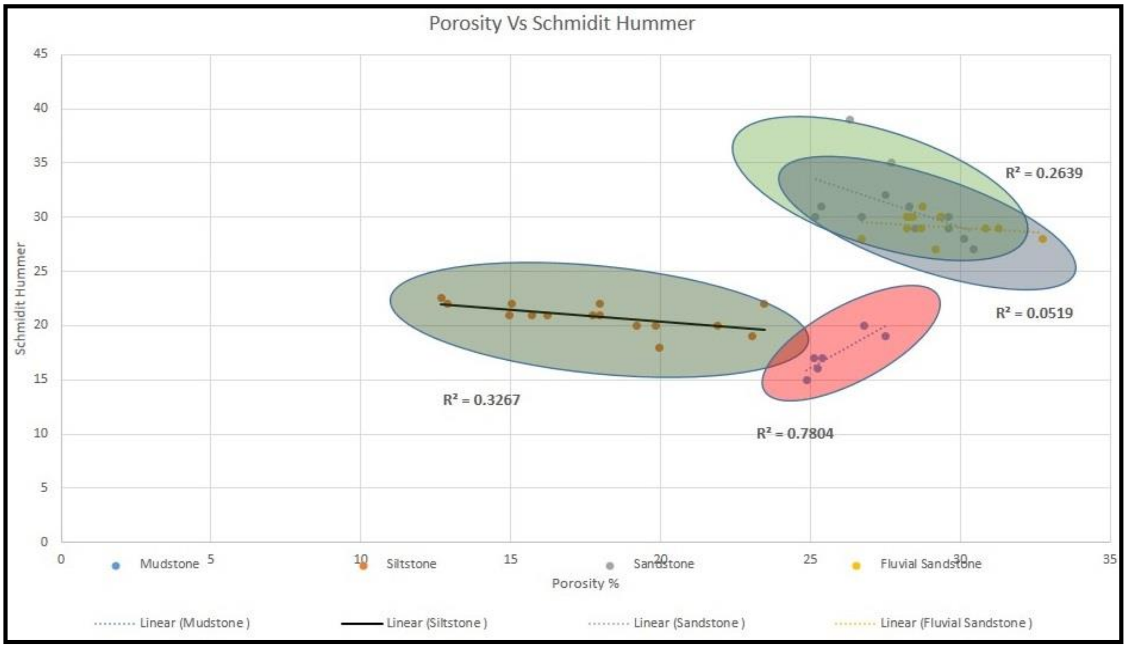

Figure 5.16 Scatter graph showing the relation between porosity and Schmidt Hammer average.

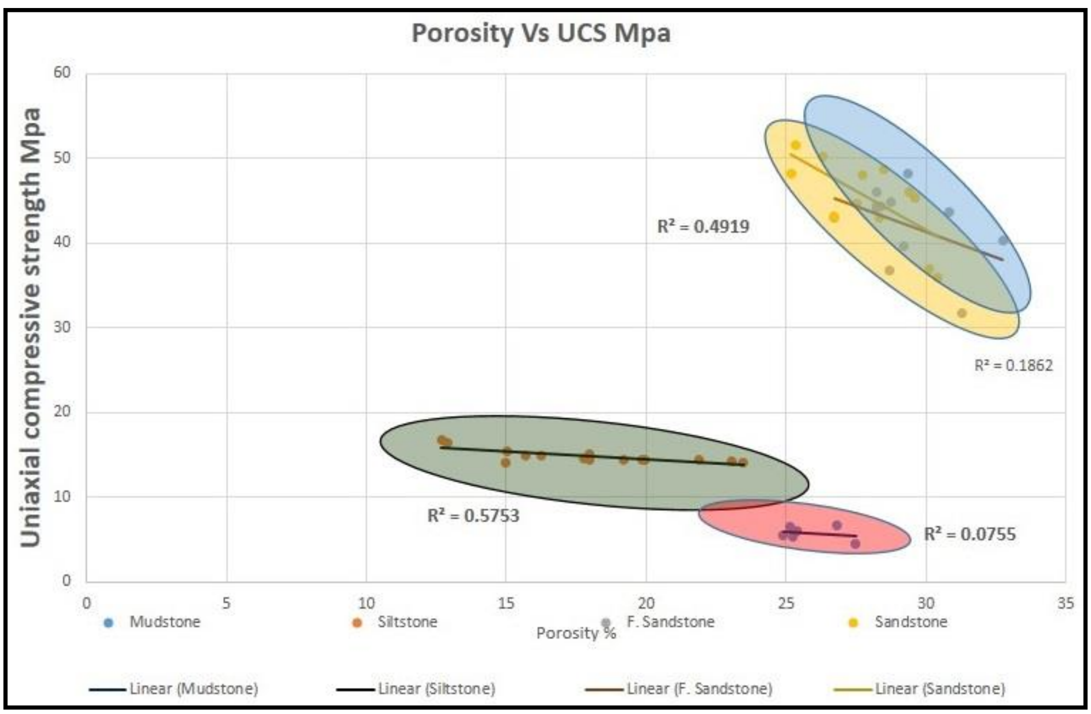

Figure 5.17 Scatter graph for the relation between porosity and uniaxial compressive strength.

The inverse relation between porosity and strength tests is evident in the cross plots and the lithofacies appear as clusters based on the change in porosity and geomechanical tests. The rock strength decreases with increasing porosity values.

The p-wave velocity is one of the major properties in characterizing the geomechanical behavior of rock units and it is increasing with the increase of rock strength and inversely proportional to the porosity. The (figure 5.16) below displays the relation between porosity and p-wave velocity. The cross- plot defines clear grouping of lithofacies having different relations between porosity and p-wave velocity, as shown below.

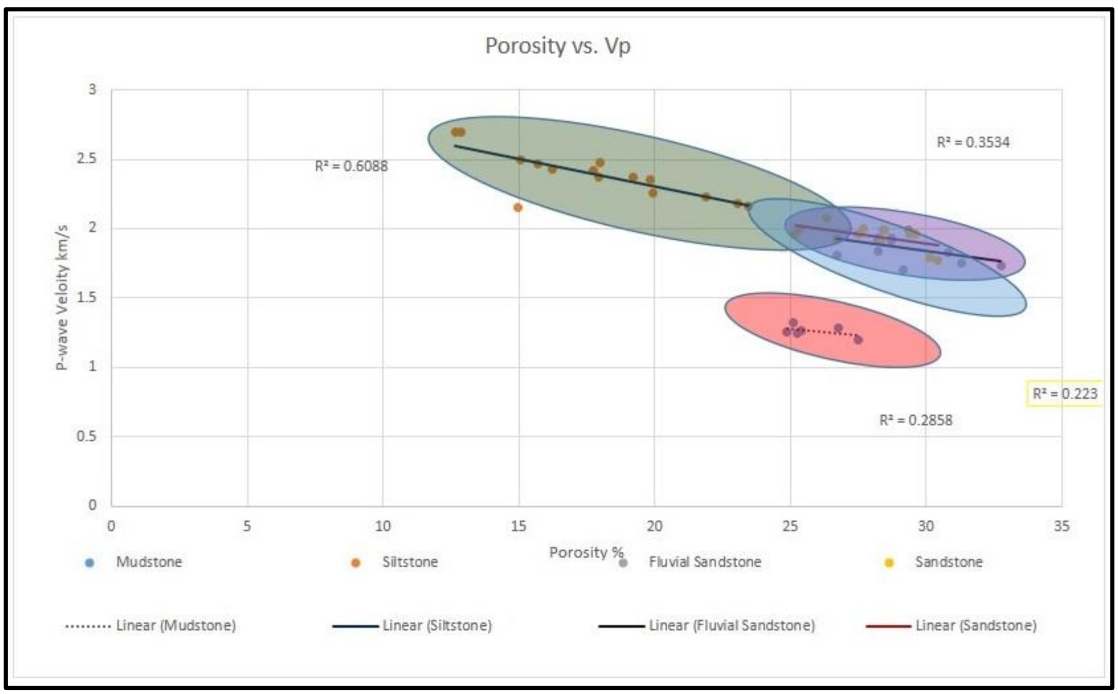

Figure 5.18 Scatter graph of the relation between porosity and P-wave velocity.

The p-wave velocity for the measured samples is proportionally related to the point load and Schmidt hammer measurements. Therefore it increases with increase of rock strength and is inversely proportional to the porosity.

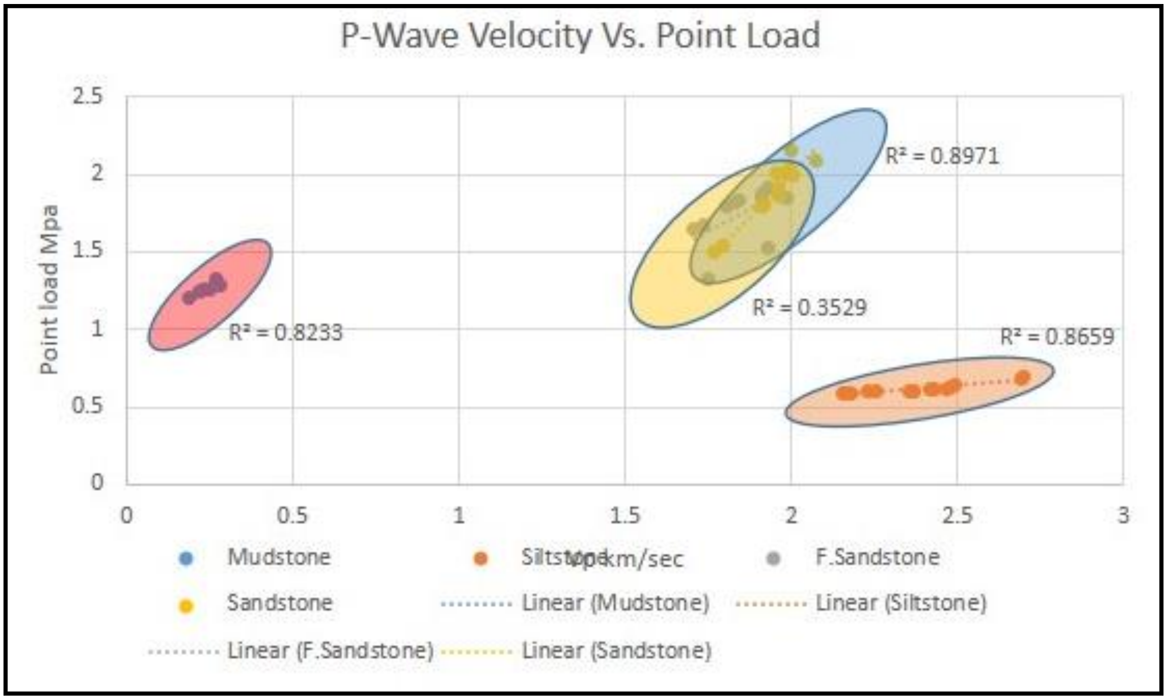

Figure 5.19 Scatter graph of the relation between P-wave velocity and point load

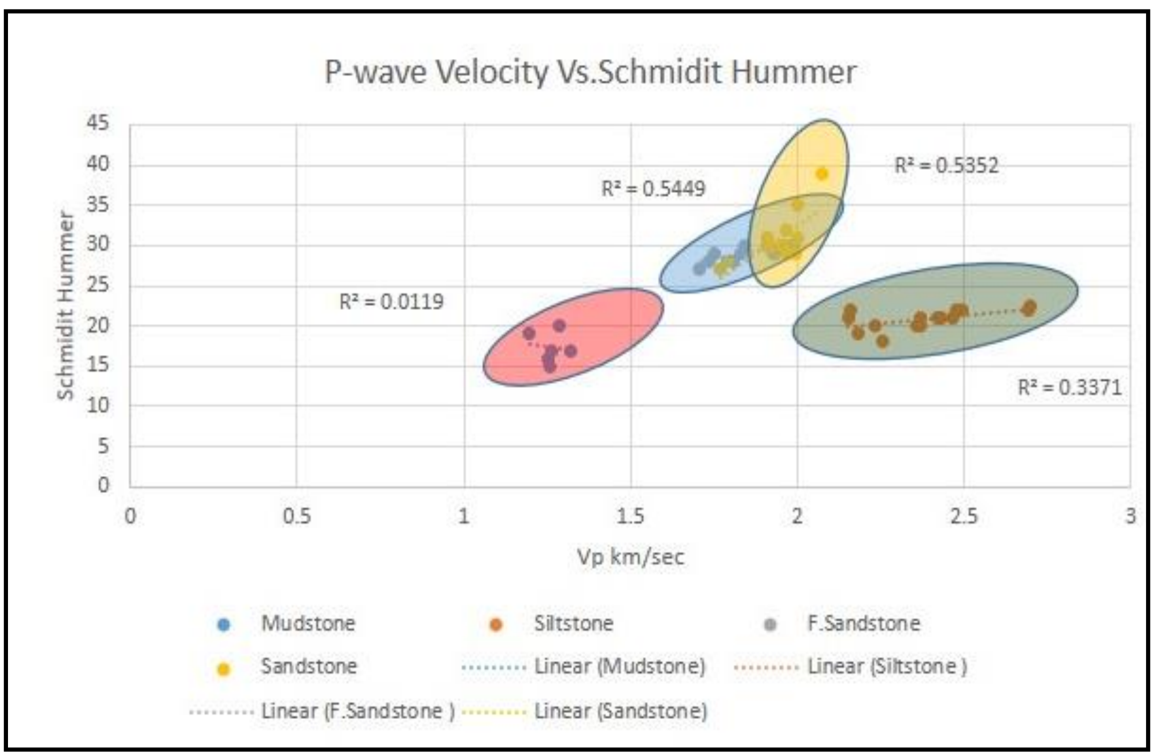

Figure 5.20 Scatter graph of the relation between P-wave velocity and point load.

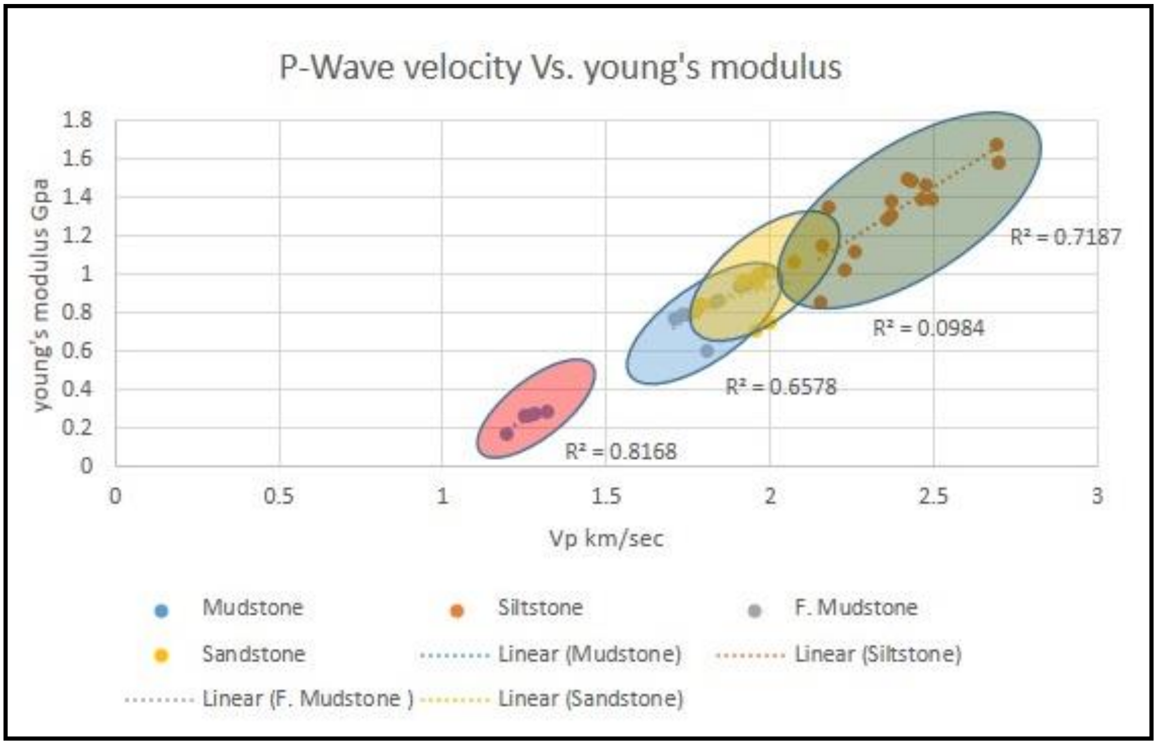

Figure 5.21 Scatter graph for P-wave velocity versus point load.

The grouping in the plotted graphs corresponds to distinct parts of the rock with different lithology and different geomechanical properties. This grouping can be used to define the mechanical units based on additional tests and measurements such as gamma ray measurements, point load values and uniaxial compressive strength tests.

The Schmidt hammer test gives qualitative indication for rock hardness, which can be used with other parameters to define the geomechanical properties for the lithologic units. The Schmidt hammer gives higher readings for the harder rock, which coincides with higher reading for point load and Young's modulus. The figures below indicate proportional relation of Schmidt hammer with point load test and Young's modulus.

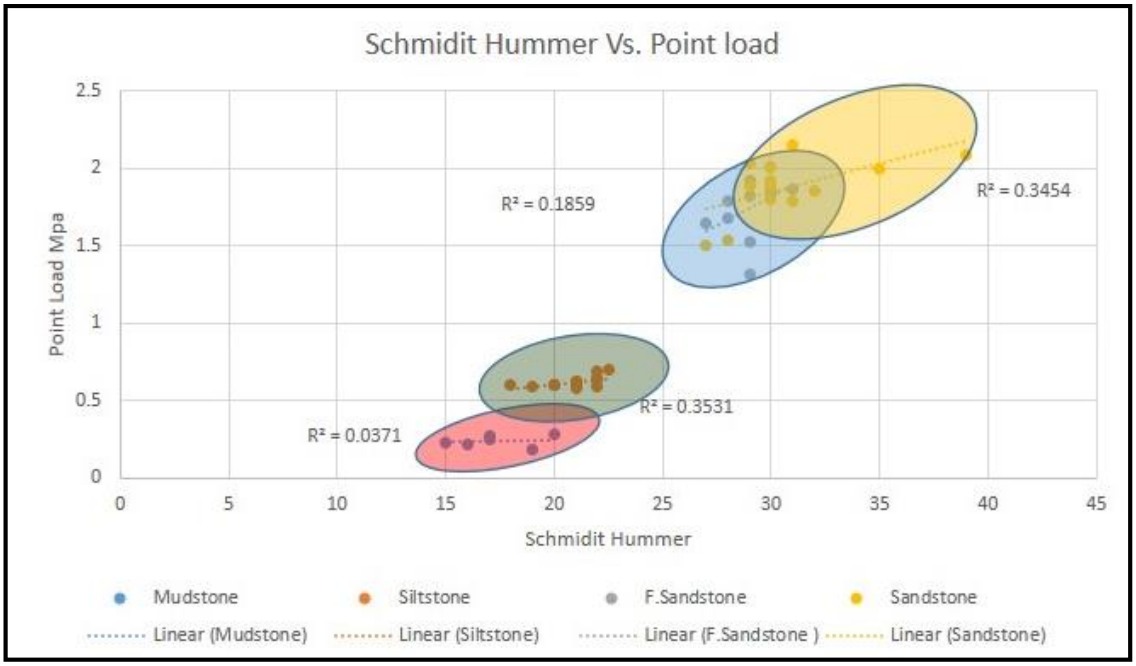

Figure 5.22 Scatter graph showing Schmidt hammer versus point load.

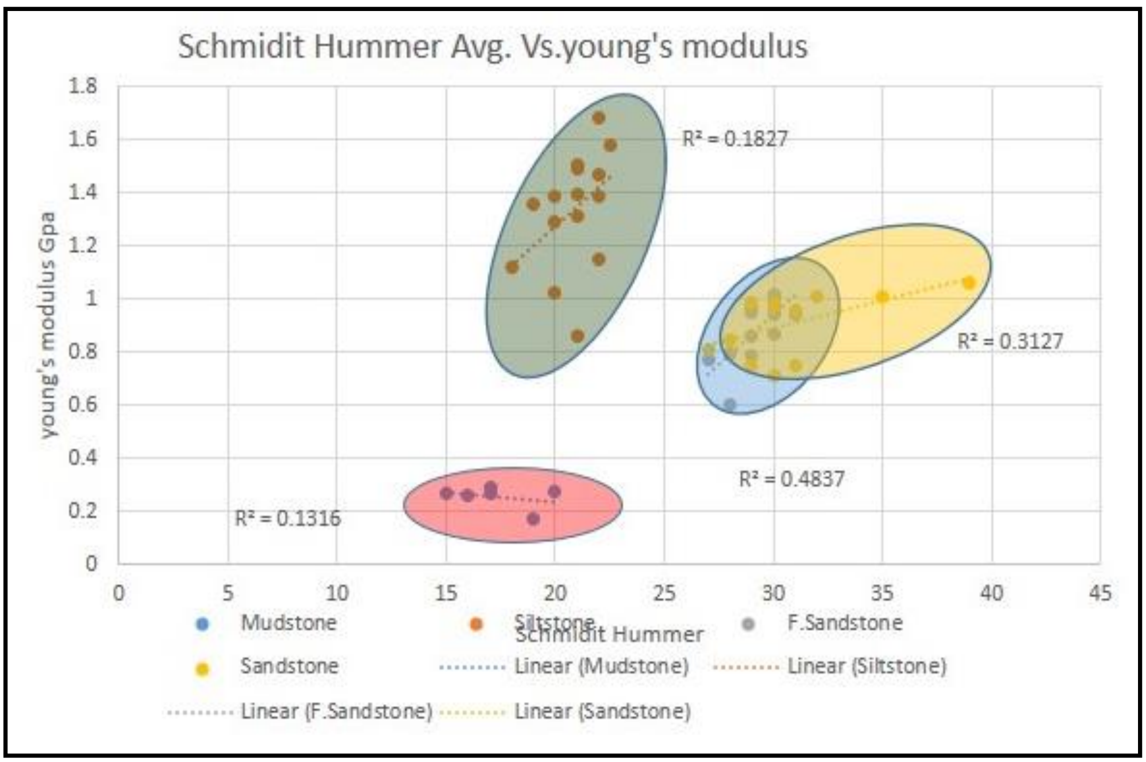

Figure 5.23 Scatter graph showing the relation between Schmidt Hammer and Young's modulus.

Young's modulus (modulus of elasticity (E)) is a proportionality constant that relates stress and ~~the~~ strain. Therefore, Young's modulus is proportionally related to the rock strength. The scatter graph below illustrates the relation between Young's modulus, point load and uniaxial compressive strength.

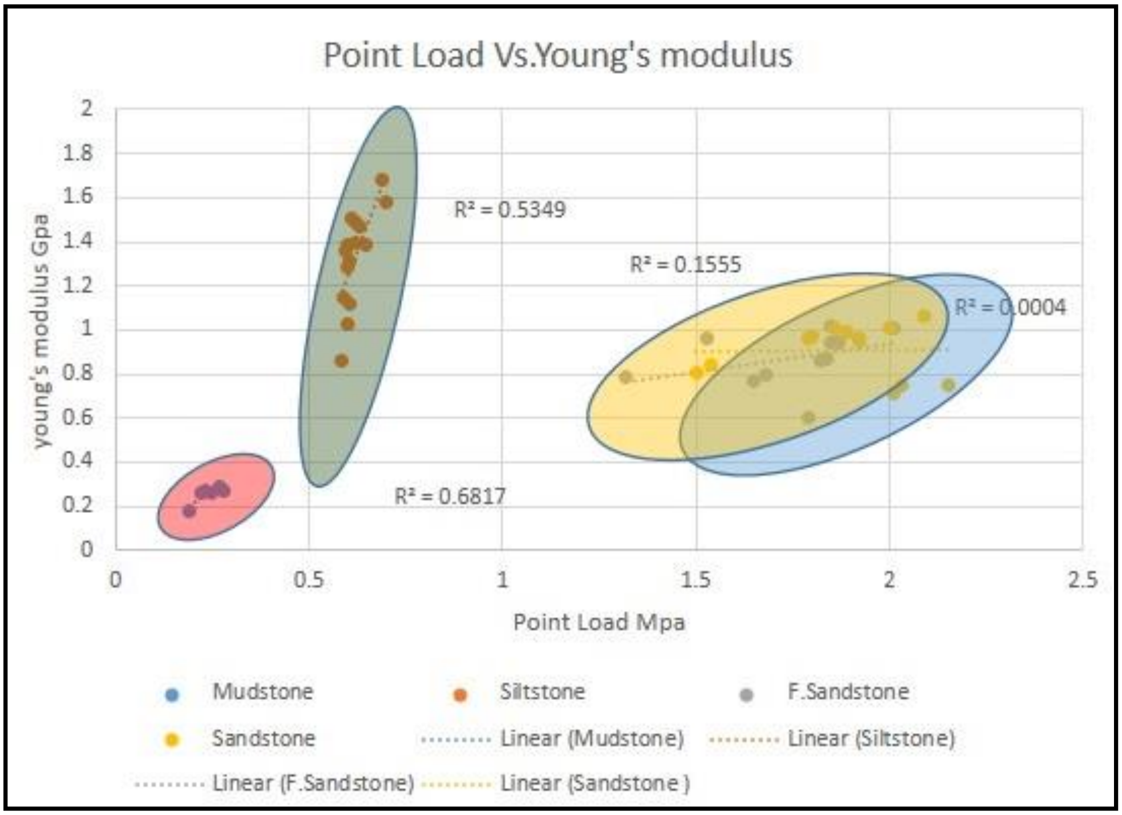

Figure 5.24 Young's modulus versus point load.

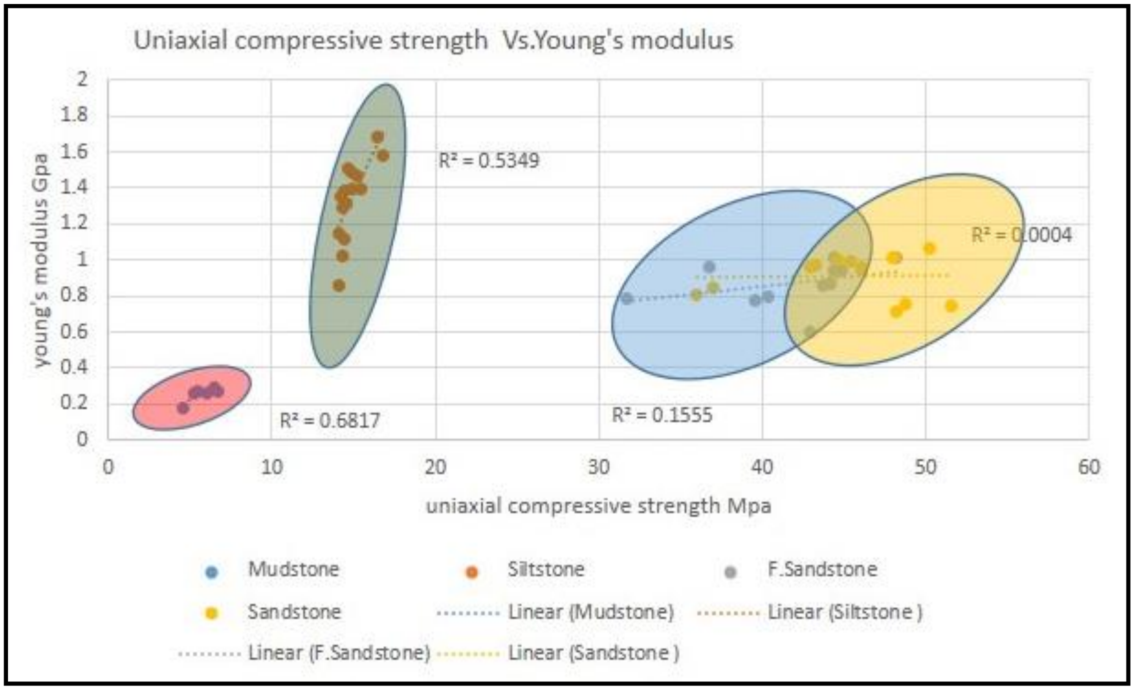

Figure 5.25 Young's modulus versus uniaxial compressive strength.

The uniaxial compressive strength values for the studied area expressed a group pattern for the lithogic units. Lucas (2002) proposed a table that classified the rocks according to uniaxial compressive strength value, from very high uniaxial compressive strength to extremely low uniaxial compressive strength, which coincides with very high strength rock properties to extremely low strength rock properties. The tables below show the average uniaxial compressive strength values together with Lucas classification.

Classification	UCS (MPa)
Very High	>200
High	100 - 200
Medium	50 - 100
Low	25 - 50
Very Low	10 - 25
Extremely Low	<10

Table 5.1 Lucas (2000) classification for uniaxial compressive strength values.

Lithology	Average UCS (Mpa)	Lucas classification
Yellowish sandstone lithofacies	45.1	Low
Fluvial sandstone lithofacies	42.26	Low
Siltstone lithofacies	14.8	Very low
Mudstone lithofacies	5.76	Extremely low

Table 5.2 Uniaxial compressive strength average results.

The lithological units had uniaxial compressive strength values ranging from low strength to extremely low strength.

The point load values are classified according to (Bieniawski, 1975) classification~~s~~.

Classification	Point Load Index – $I_{s(50)}$ (MPa)
Very High Strength	>8
High Strength	4 - 8
Medium Strength	2 - 4
Low Strength	1 - 2
Very Low Strength	<1

Table 5.3 (Bieniawski, 1975) classifications for rock strength

Lithology	**Point Load Average Is(50)**	**Bieniawski, 1975 Classification**
Yellowish glacial sandstone lithofacies	1.88	low strength
Fluvial sandstone lithofacies	1.76	low strength
Siltstone lithofacies	0.6	Very low strength
Mudstone lithofacies	0.24	Very low strength

Table 5.4 Bieniawski, 1975 Classification for point load average values

According to the Bieniawski, 1975 Classification and Lucas (2000) classification the lithologic units express low strength in the sandstone lithofacies to very law strength in mudstone lithofacies. The strength of the studied rock units is reduced along the weakness plane represented by the boundaries between different lithologies and along the lineation planes (Figure 4-32).

According to the fracture data, geomechanical cross plots and vertical plots the relation between lithostratigraphy and geomechanical properties of Sarah Formation is summarized in the figures below. Five geomechanical units are indicated, with different gemechanical and lithostratigraphical properties.

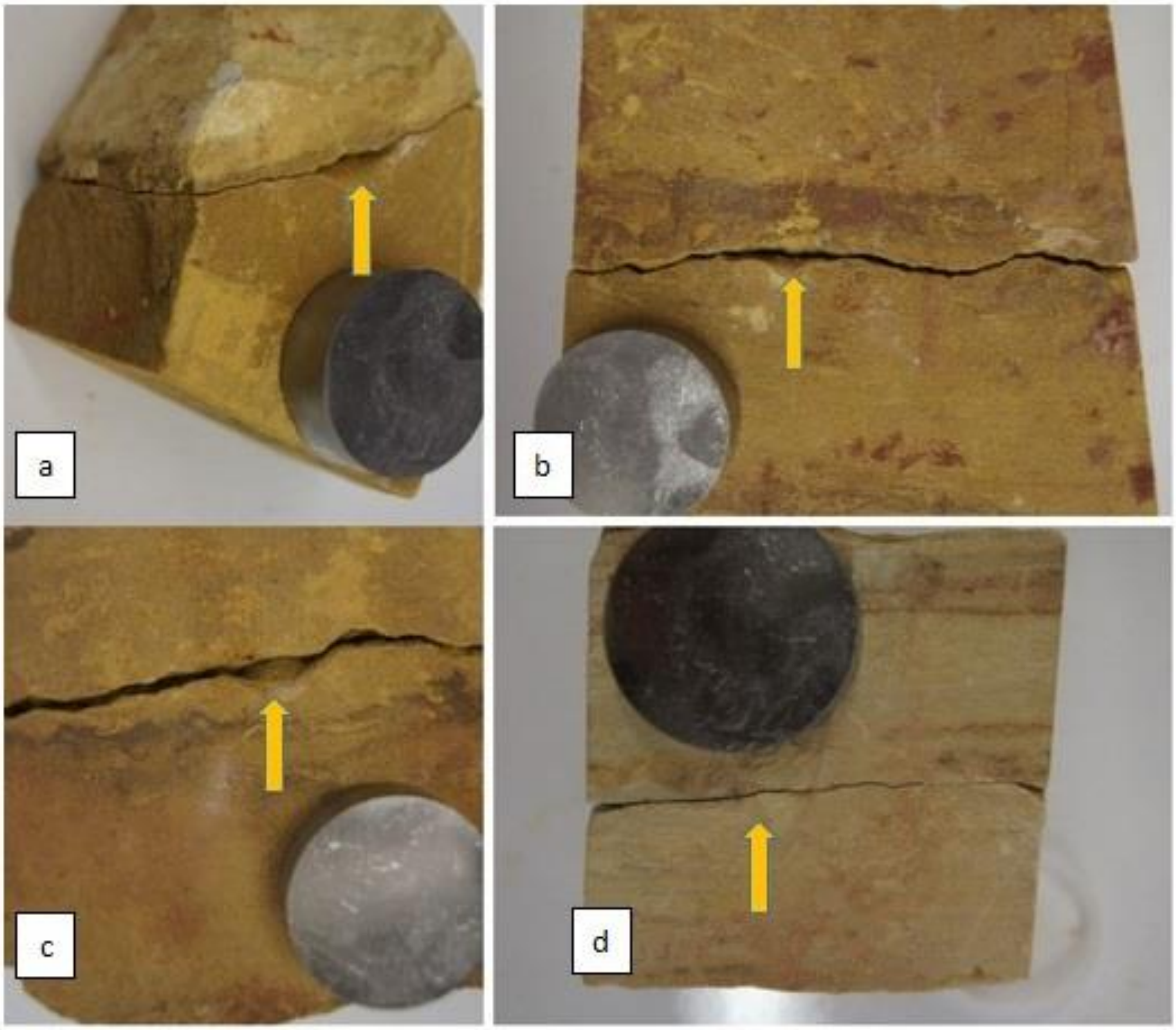

Figure 26 Photograph for point load failure along weakness planes and lithofacies boundaries

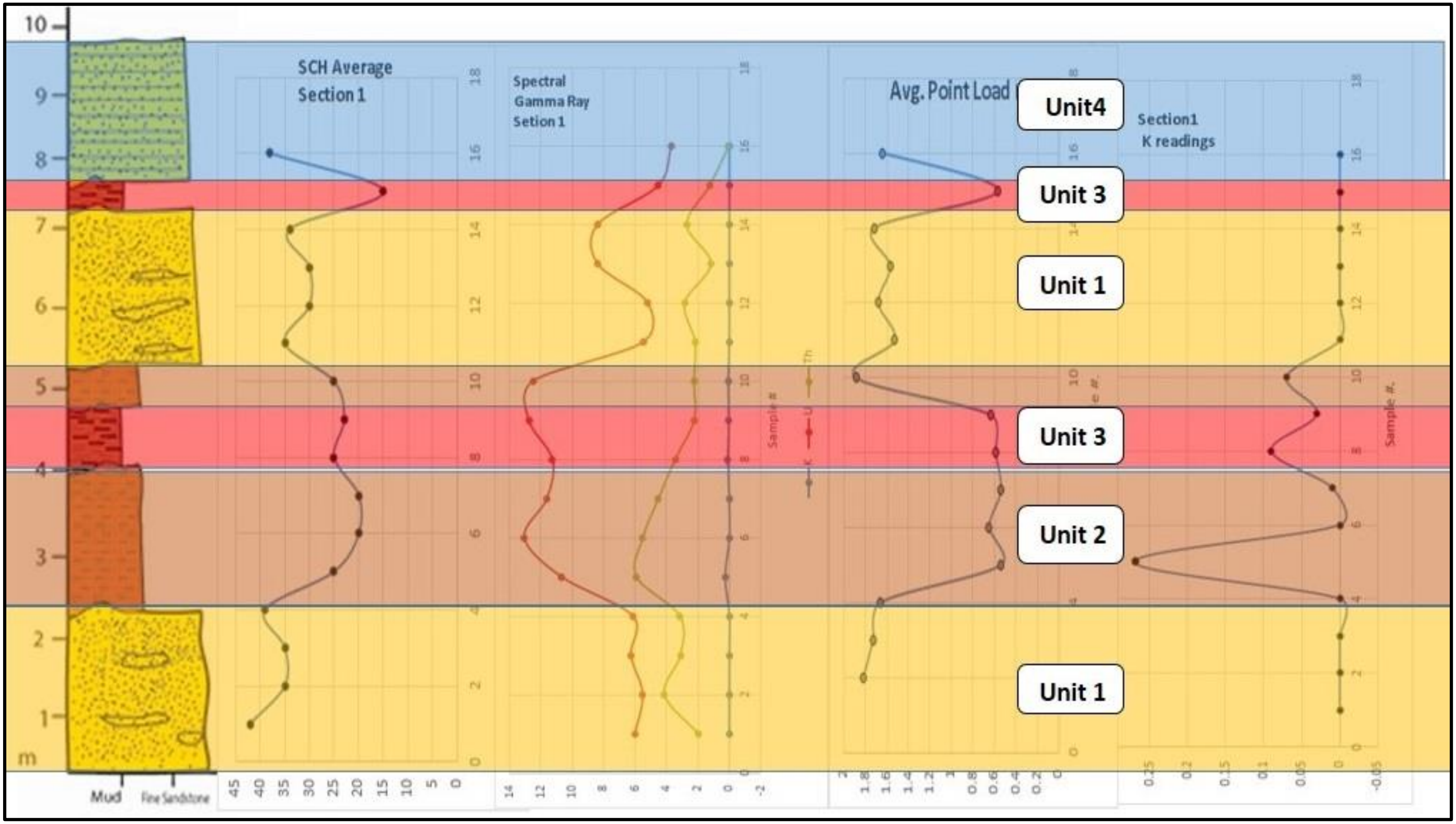

Figure 5.27 Vertical section for geomechanical units classification at Sarah paleochannel.

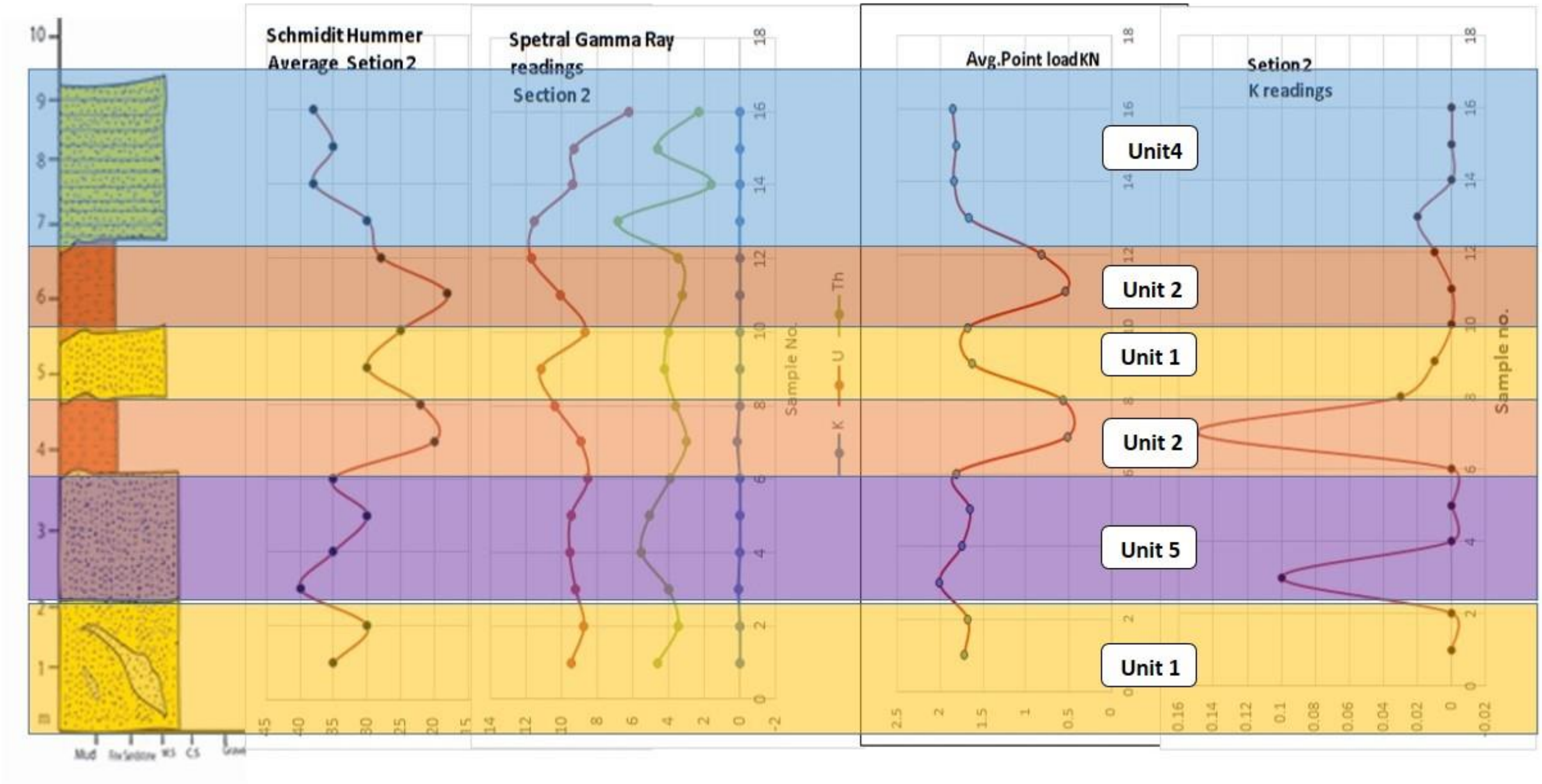

Figure 5.28 Vertical section show the geomechanical unit classification at Sarah paleochannel.

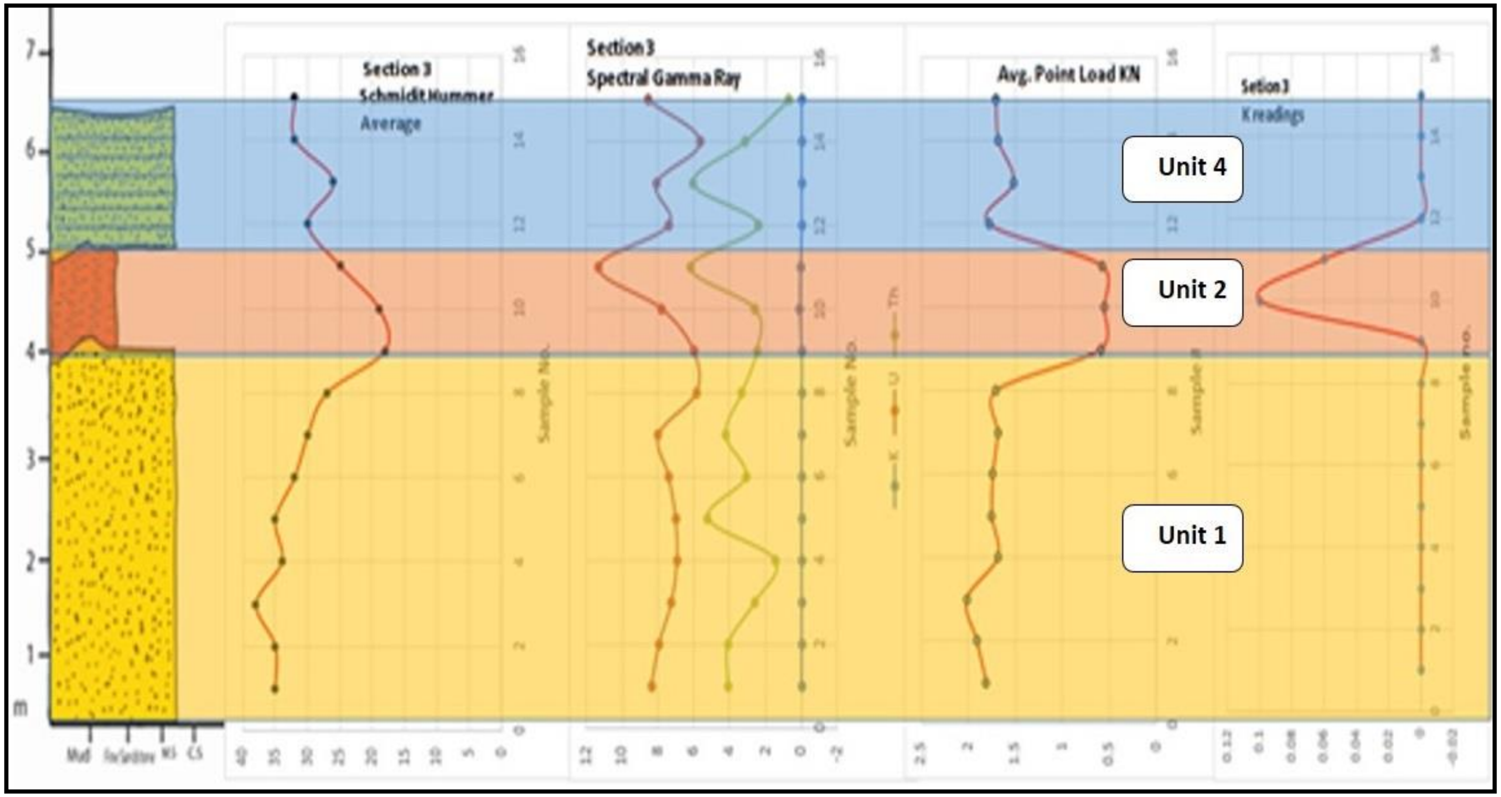

Figure 5.29 Vertical section for geomechanical units classification at Sarah paleochannel

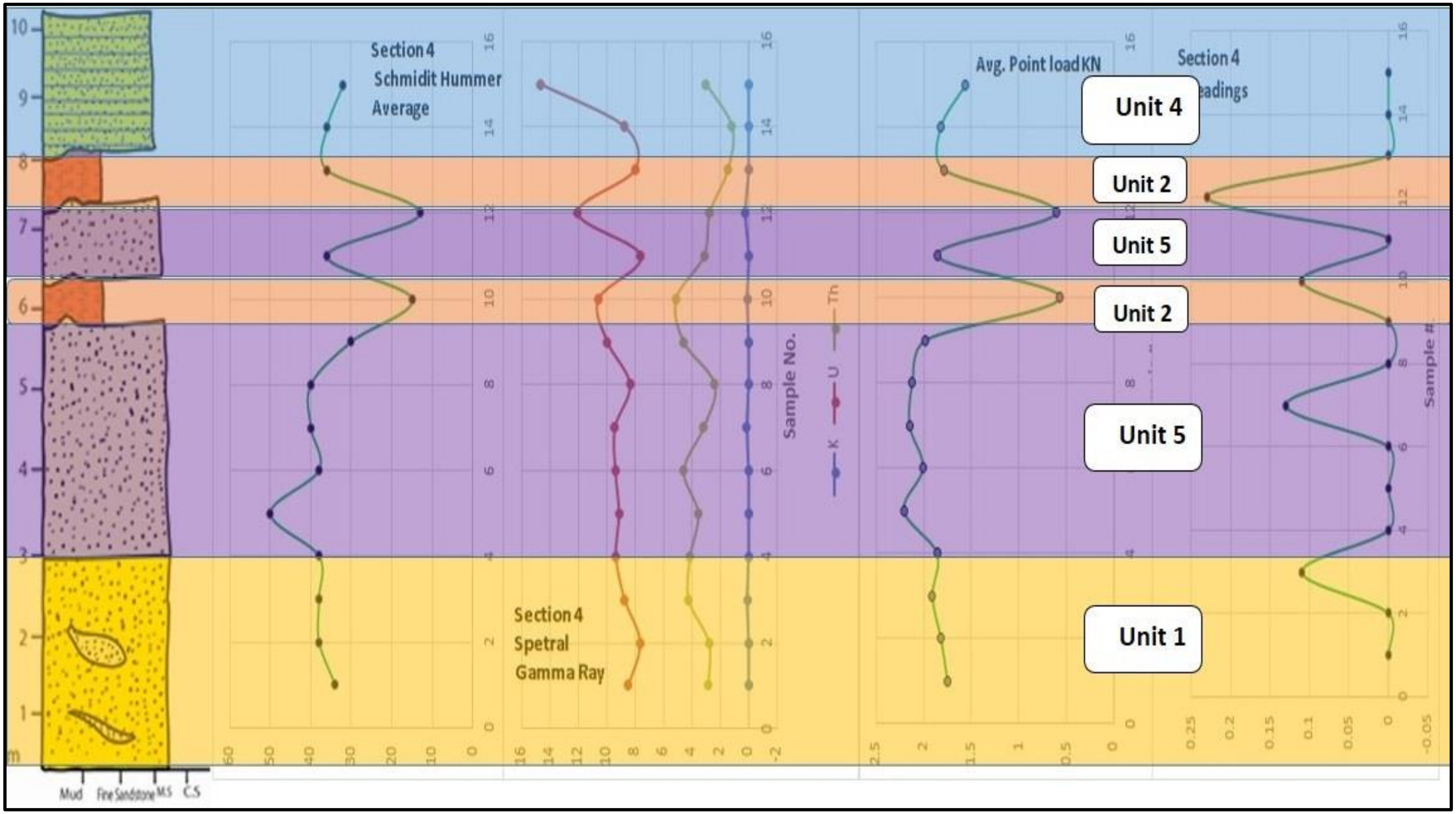

Figure 5.30 Vertical section for geomechanical units classification at Sarah paleochannel.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This study was conducted to investigate the relationship between lithostratigraphy and geomechanical properties of Sarah Formation. The studied outcrop occurred at Rawd Al-Jawa paleovalley in Qaseem area. The work consists of three parts sedimentological, fracture and geomechanical investigations. Sedimentological properties were investigated from field and laboratory measurements. The geomechanical investigation includes, point load test, Schmidt hammer, uniaxial compressive strength, velocity measurements and fracture analysis. The sedimentological studies were conducted on four outcrop sections and revealed five main lithofacies namely (a) yellowish brown, poorly sorted, medium to coarse, diamictite interbedded with ferruginous sandstone lithofacies, (b) brownish yellow, finely interbedded, slumped siltstone lithofacies, (c) slumped mudstone lihofacies, (d) white, medium to coarse grained, poorly sorted sandstone lithofacies and (e) yellow, medium to fine grained, moderately sorted, laminated fluvial sandstone lithofacies. Sedimentological and structural model constructed helped to understand different types and scales of heterogeneity. The sedimentological glacial features was indicated by the presence of fractured and deformed quartz with clear striation resulted from the glaciation and poorly sorting sediments. And by outcrop deformed and erosive boundaries. At outcrop scale, the slumping and folding also were found with 1 to 4 meter diamictite boulders which give strong evidence for glaciation process. The fractures in the studied outcrop are mostly oriented NW, SE or EW directions ranging from open fractures to closed fractures. The studied fractures revealed three modes of stress regime which are, mode 1 (opening mode), mode 2 (sliding mode) and mode 3 (shear mode), which all reflect different stresses regime at the glacial paleochannel. The relationship between fracture and lithofacies studied showed different fracture sets confined to specific lithofacies and this resulted from the change in geomechanical and elastic properties of different lithofacies. The fracture properties changed from closed, resistive to open fracture based on mode regime and lithofacies changes. The closed fracture sets mainly resulted from sliding mode regime, which fill the fracture with iron oxides and characterized by very low porosity, which act as a seal separating between different glacial push moraines in the formation. The closed fractures sets confined mainly to SE, NW fracture sets. The resistive fractures resulted mainly from mode 3 regime, which fills the fractures with calcite and iron oxides. This type of fractures are mainly confined to E, W fractures. The opened fractures resulted from mode 1 regime and mainly confined to S-N fracture set, which enhances for reservoir quality. Structural and lithological model conducted helped to provide a clear understanding for the fracture distribution and their relation to the lithological distribution. The relationship between geomechanical properties and lithostratigraphy studied by integrating geomechanical with petrophysical parameters using cross plots with respect to lithofacies and vertical sections. Geomechanical parameters used to investigate these relationship are Schmidt hammer test, point load test, uniaxial compressive strength, velocity measurements and the moduli derived from those parameters. The petrophysical parameters used are porosity and permeability. The cross plots between petrophysical and geomechanical parameters revealed on four lithofacies zonation. The porosity of the studied sections is inversely proportional with the geomechanical parameters as revealed from strength test such as point load test, p-wave and s-wave velocity, Schmidt hammer test and uniaxial compressive strength. The results of the cross plots are well correlated with (Lucas, 2002) and (Bieniawski, 1975) strength classification. The relationship between geomechanical properties and lithostratigraphy, defined based on the previous data analysis and the spectral gamma ray response for the four vertical sections, revealed five geomechanical units that have direct relationship to the lithostratigraprhy. Lithostratigraphical and structural model established in study, helped to understand the relationship between lithofacies and geomechanical properties. The vertical and horizontal lithological heterogeneity understood from the model, can also help to predict the nature of the glaciofluvial reservoir in the subsurface. The understanding of vertical and horizontal heterogeneity of lithostratigraphy is expected to help to predict the shape and nature of the Sarah reservoir in the subsurface. the fracture study on outcrop showed that fracture direction and characterization are well correlated with those reported in the subsurface by Bukhamseen et al.|(2010).

6.1 Recommendations:

On the basis of my study the following recommendations can be made for future work for Sarah Formation

1- Detailed study for facies distribution of Sarah Formation.
2- Detailed study of the heterogeneity of Sarah Formation reservoir in regional scale.
3- Extend the area of the study to include all Sarah paleovalleys and create a regional map for the geomechanical properties.
4- Detailed study for fracture characteristics and the nature of diagenetic processes that fill the fractures.
5- Integration of outcrop studies with the subsurface data.

References

Adams, J.A.S. & Weaver, C.E., 1958. Thorium-to-Uranium ratios as indicators of sedimentary processes: example of concept of geochemical facies. American Association of Petroleum Geologists Bulletin.

Alikarami, R., Torabi, A., Kolyukhin, D., & Skurtveit, E., 2013. Geostatistical relationships between mechanical and petrophysical properties of deformed sandstone. International Journal of Rock Mechanics and Mining Sciences, 63, 27–38. doi:10.1016/j.ijrmms.2013.06.002.

Al Kharusi, L., 2009. Correlation between high resolution sequence stratigraphy and mechanical stratigraphy for enhanced fracture characteristic predictio. *Thesis Dissertation*.

Al-Mahmoud and Al-Ghamdi, 2010. Overview of Tight Gas reservoir in Saudi Arabia. 2nd Middle East Tight Gas Workshop, Bahrain. Association, 116, 331-347.

American Society of Testing Materials, 1980. Annual book of ASTM standards – natural building stones. Soil and rock, part 19. ASTM Publications, Philadelphia, 634 pp.

Bellian, J. A., Kerans, C., & Jennette, D. C., 2005. Digital Outcrop Models: Applications of Terrestrial Scanning Lidar Technology in Stratigraphic Modeling. *Journal of Sedimentary Research*, *75*(2), 166–176.

Broch EM, Franklin JA, 1972. The point load strength test. Int J Rock Mech Min Sci 9:669–697.

Brook, N., 1985. The equivalent core diameter method of size and shape correction in point load test. Int. J. Rock Mech. Min. Sci. Geomech. Abstr. 22, 61–70.

Broch, E., and Franklin, J.A., 1972. The point-load strength test: International Journal of Rock Mechanics and Mining Sciences, v. 9, p. 669-693.

Brown, E.T. (Editor), 1981. Rock Characterization, Testing and Monitoring, ISRM Suggested Methods: England, Pergamon Press, 211 p.

Clarkson, C. R., Jensen, J. L., Blasingame, T. A., & Texas, A., 2011. SPE 145080 Reservoir Engineering for Unconventional Gas Reservoirs : What Do We Have to Consider ?.

Corbett, K., Friedman, M. and Spang, J., 1987. Fracture development and Mechanical Stratigraphy of Austin Chalk, Texas; The American Association of Petroleum Geologists Bulletin, v. 71, No. 1, p. 17-28.

Dewers, T., Newell, P., Broome, S., Heath, J., & Bauer, S., 2014. Geomechanical behavior of Cambrian Mount Simon Sandstone reservoir lithofacies, Iowa Shelf, USA. *International Journal of Greenhouse Gas Control*, *21*, 33–48. doi:10.1016/j.ijggc.2013.11.010.

Engelder, T., Gross, M. and Pinkerton, P., 1997. An Analysis of joint development in thick sandstone beds of the Elk Basin Anticline, Montana-Wyoming; Rocky Mountain Association of Geologists, Fractured Reservoirs: Characterization and Modeling Guidebook.

Grant, N. S. F., & Cmmi, A., 2011. LiDAR and optical imaging for 3-D fracture orientations.

Gross, M. R., 1995. Fracture partitioning: Failure mode as a function of lithology of the Monterey Formation of coastal California: Geological Society of America Bulletin, v. 107, no. 7, p. 779-792.

Ghienne, J. F., 2011. The Late Ordovician glacial record: State of the art. Ordovician of the World. Cuadernos del Museo Geominero, 14: 13- 19.

Goodman, R.E., 1980. Introduction to Rock Mechanics: New York, John Wiley & Sons, 478 p.

Hawkes, I., and Mellor, M., 1970. Uniaxial testing in rock mechanics laboratories: Engineering Geology, v. 4.

Hassan, M., Hossin, A. & Combaz, A., 1976. Fundamentals of the differential gamma ray log – Interpretation technique. Society of Professional Well Log Analysts 17th Annual Logging Symposium, June 9–12, 1976.

Hsieh, Y.-M., Li, H.-H., Huang, T.-H., & Jeng, F.-S., 2008. Interpretations on how the macroscopic mechanical behavior of sandstone affected by microscopic properties—Revealed by bonded-particle model. *Engineering Geology*, *99*(1-2), 1–10. doi:10.1016/j.enggeo.2008.01.017.

Hussain, M., El Hassan, W. M., & Abdulraheem, A., 2006. Controls of grain-size distribution on geomechanical properties of reservoir rock—A case study: Cretaceous Khafji Member, Zuluf Field, offshore Arabian Gulf. *Marine and Petroleum Geology*, *23*(6), 703–713.

Le Heron, D.P., Craig, J. and Etienne, J.L., 2009. Ancient glaciations and hydrocarbon accumulations in North Africa and the Middle East. Earth-Science Reviews, 93(3): 47-76.

McClure, H.A. 1978. Early Paleozoic Glaciation in Arabia, Paleogeography, Paleoclimatology, Paleoecology, v. 26.

Miller, R.P., 1965. Engineering classification and index properties for intact rock. PhD Thesis, University of Illinois.

Millson, J. A., Mercadier, C.G.L., Livera, S. E. and Perters, J., 1996. The lower Paleozoic of Oman and its context in the Evolution of a Gondana continental margin. Journal of Geological Society V. 153, no. 2.

Moscariello, A., Spaal, P., Jourdan, A., & Azzouni, A. H., 2009. The Ordovician Glaciation in Saudi Arabia – exploration challenges part 1. Geology outcrop, Subsurface, analogues), Search and Discovery article # 50175.

Narr, W. and Lerche, I., 1984. A Method for Estimating Subsurface Fracture density in Core, AAPG Bulletin p. 637-648.

Nelson, R.A., 1985. Geologic analysis of naturally fractured reservoirs: Gulf Publishing Co., Houston, 320p.

Petrie, E. S., Evans, J. P., Petrie, E. S., Utah, J. P. E., Main, O., & Logan, H., 2012. Comparison of Mechanical and Fracture Stratigraphy between Failed Seal Analogues.

Senalp, M., and A. Al- Laboun., 2000. New Evidence on Late Ordovician Glaciation in Central Saudi Arabia. Saudi Aramco Journal of Technology. Spring 2000.

Schenk, C.J. and Pllastro, R. M., 2000. Assessment of undiscovered oil and gas resources of the Great Rub al Khali basin by application of the total petroleum system conept-part 11, the Qusiba Paleozoic Petroleum System Geoarabia V.5, p. 175.

Vaslet, D., 1987. Early Paleozoic Glacial deposits in Saudi Arabia, a Lithostratigraphic Revision, Saudi Arabia Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources, Jeddah. Technical Record, BRGM-07-1, 24p.

Vaslet, D., 1989. Late Ordovician Glacial deposits in Saudi Arabia: A Lithostratigraphic Revision of the Early Paleozoic succession. Saudi Arabia Ministry of Petroleum and Mineral Resources, Deputy Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources~~m~~ Professional Papers, no. PP-3, p, 15-44.

Vaslet, D., 1990. Upper Ordovician Glacial Deposits in Saudi Arabia. Episodes v. 13, p. 147-161.

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2- Types and nature of fractures associated with glacio-fluvial Sarah Formation, Central Saudi Arabia